PINGU* and the Neutrino Mass Hierarchy

Fundamental Particle Physics in the Ice with Atmospheric Neutrinos

*Precision IceCube Next Generation Upgrade

Particle Physics Project Prioritization Panel (P5)

December 2-4, 2013

IceCube-PINGU Collaboration

Spokesperson: Olga Botner

Deputy Spokesperson: Tyce DeYoung

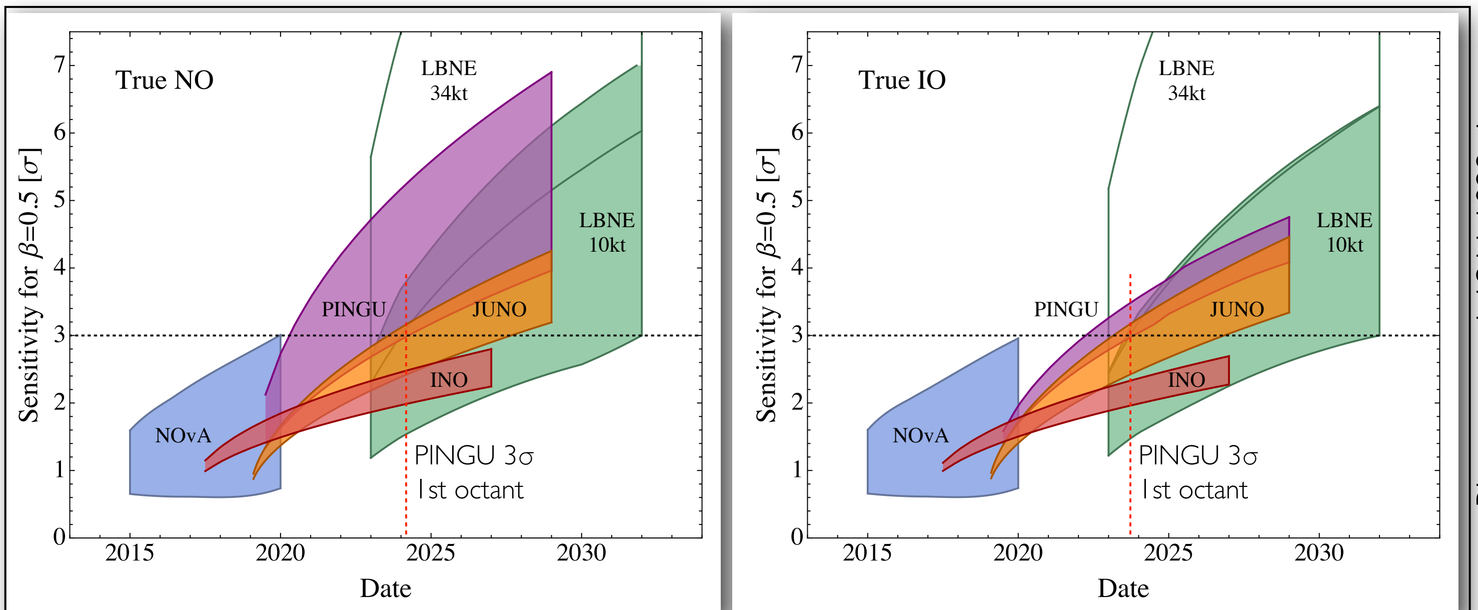
PINGU Co-Leads: Darren Grant, Doug Cowen

IceCube PI: Francis Halzen

Running and Proposed NMH Experiments

- PINGU, HyperK, INO
  - NMH sensitivity for all δ_{CP}
- NOvA, T2K
  - NMH sensitivity for limited δ_{CP} range
- JUNO (funded) and RENO-50 (likely funded)
  - NMH sensitivity for all θ_{23}, δ_{CP}

- LBNE (approved)
  - measure both NMH and δ_{CP}
- Indirect methods:
  - Cosmic surveys (optical, CMB)
  - SNe neutrino burst
  - $0\nu\beta\beta$ decay



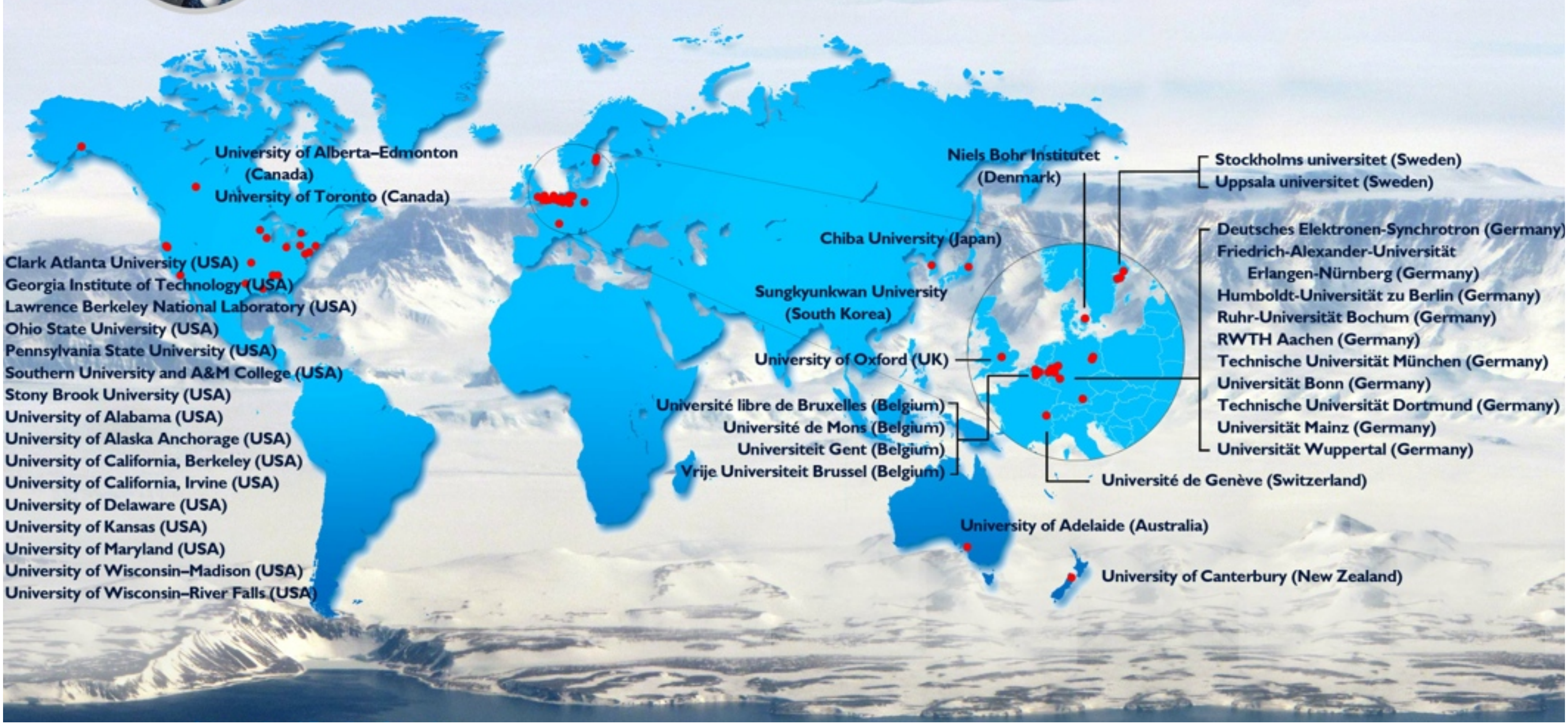
Blennow et al. 1311.1822v1

Width of bands depends on range of parameters (for PINGU: $40<\theta_{23}<50$).
We assume 1st octant ($\theta_{23}=40$), the lower PINGU boundary in both plots.

N.B.: Atmospheric, reactor and accelerator-based expts. can be very complementary:

- Knowledge of NMH can enhance NOvA, LBNE sensitivity to δ_{CP}
- Combined experiments always attain 5σ NMH measurement across full δ_{CP} range; No single experiment certain to do it alone

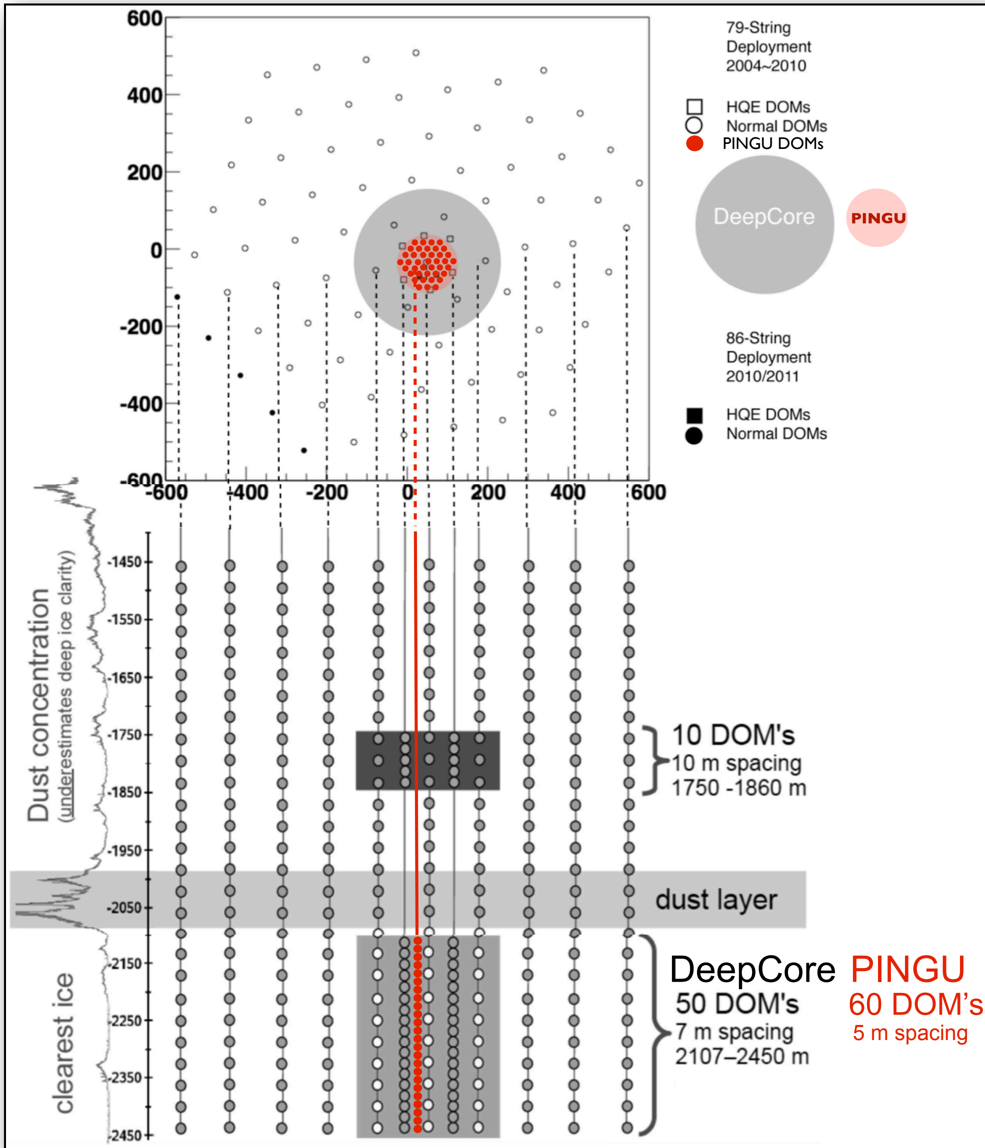
The IceCube-PINGU Collaboration

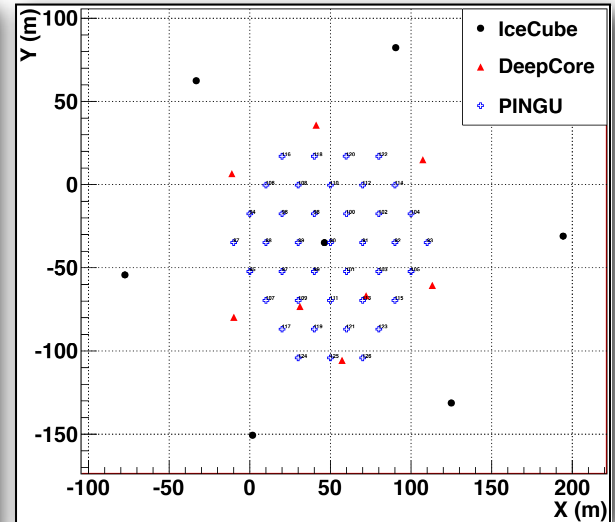


IceCube: 40 Institutions, 300 Members.
Roughly 15% active on PINGU.

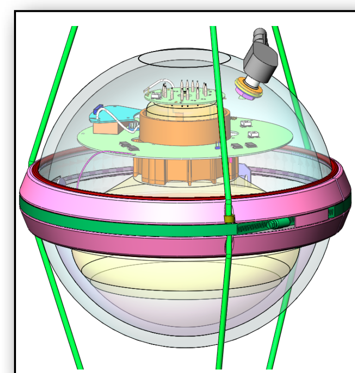
The PINGU "Baseline" Geometry

- 40 strings
- 60 PDOMs* per string
- Bottom center of IceCube
  - in-fills DeepCore
  - in clearest ice
- All NMH results that follow use baseline



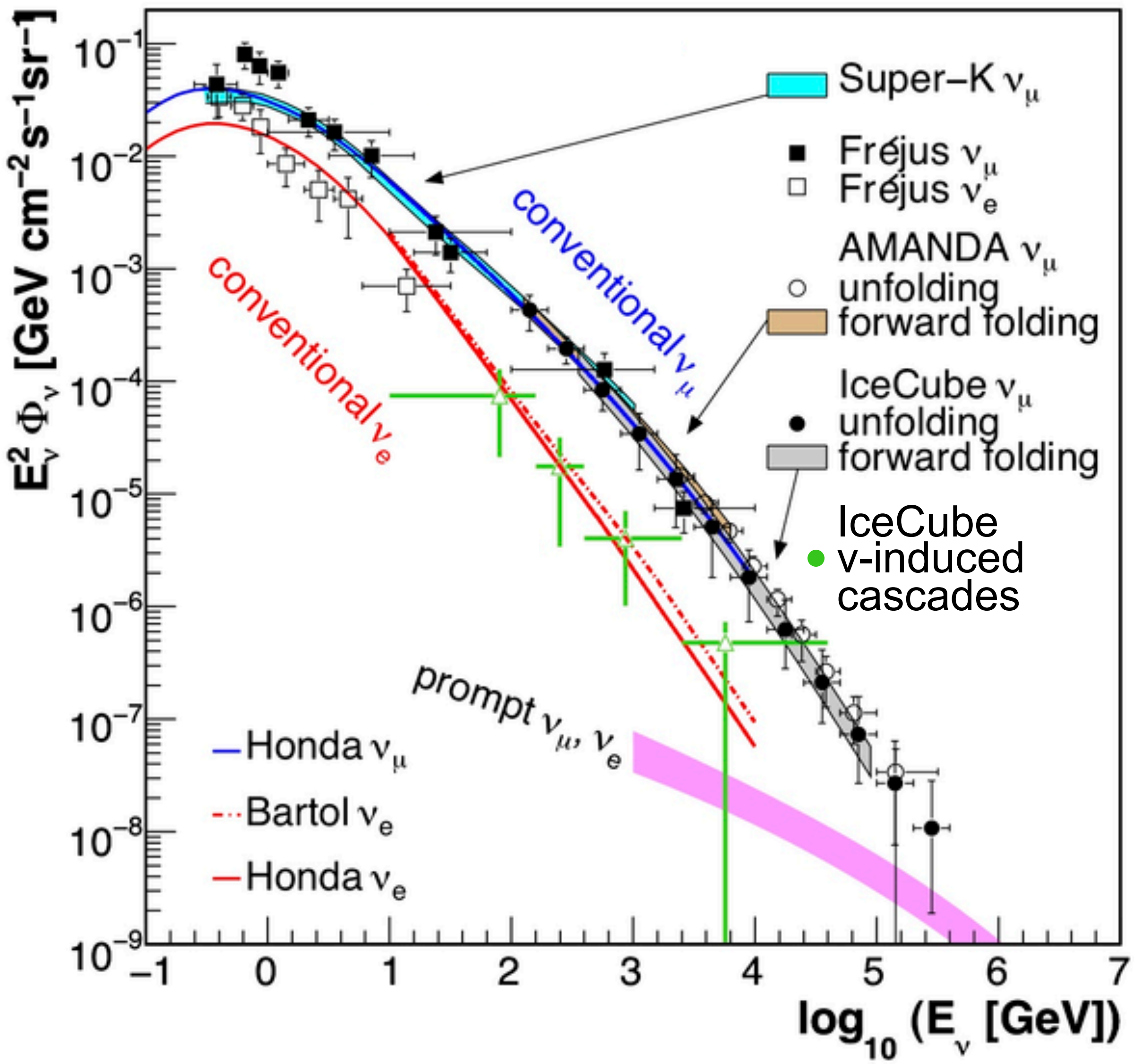


Note: The PINGU geometry has not yet been optimized!



*PINGU Digital Optical Module: HQE PMT, electronics, pressure vessel, supporting hardware; very similar to IceCube DOM.

NMH Signal from Atmospheric Flux



N(Events) Expected in PINGU per Year		
	Trigger Detector	Pass Baseline Analysis
ν_e CC	52k	26k
ν_μ CC	86k	35k
ν_τ CC	6.4k	2.7k
ν_x NC	17k	7.9k

See IceCube ν_μ oscillation result, PRL 111, 081801 (2013) and atm. ν_e detection result, PRD 83, 012001 (2011).

The NMH Signature in PINGU

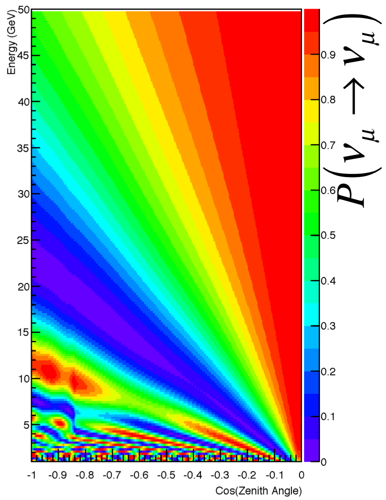
from MSW and Parametric Oscillations

MSW and Parametric Oscillations:

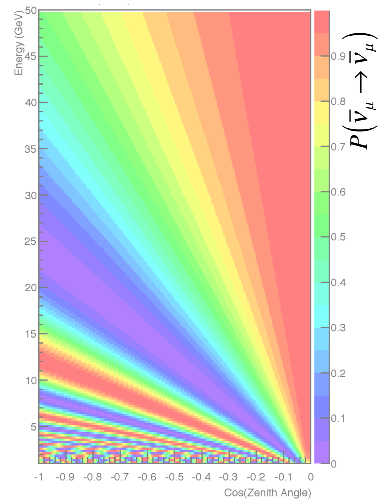
- L. Wolfenstein Phys.Rev. D17 (1978)
- S. Mikheyev and A. Y. Smirnov Prog.Part.Nucl.Phys. 23 (1989)
- E. K. Akhmedov, et al., Nucl.Phys. B542 (1999)

ν_μ anti$-\nu_\mu$

NH

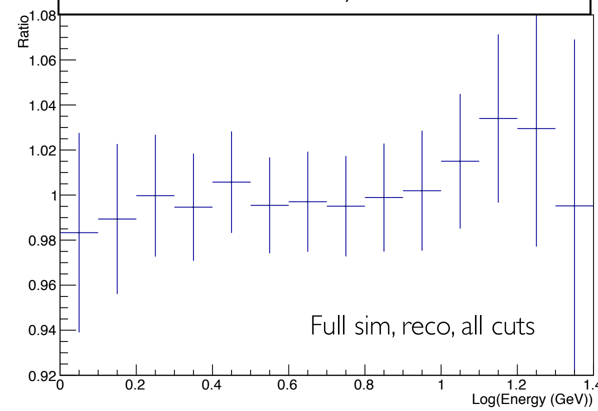


+

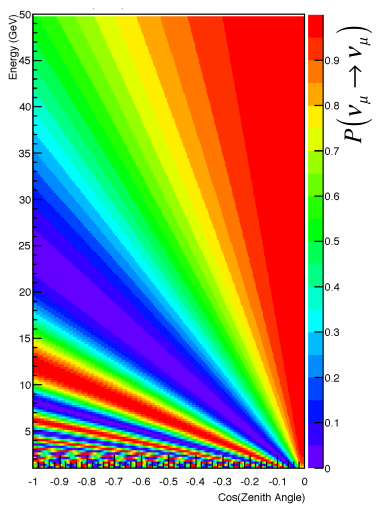


= [pattern A]

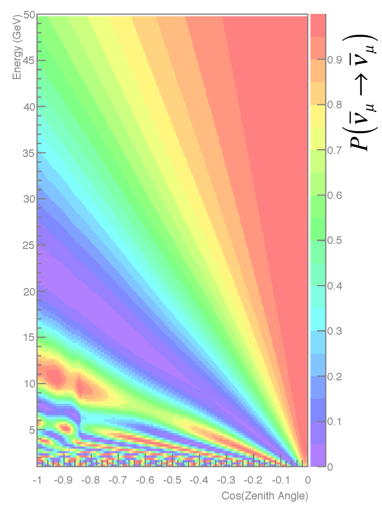
$\sigma(\nu)$~2σ(anti-ν),
$\varphi(\nu_{atm})>\varphi(\overline{\nu}_{atm})$
$\therefore$ A$\neq$B!
(True for ν_e, too)



IH



+



= [pattern B]

PINGU Signature:

- O. Mena, I. Mocioiu, and S. Razzaque, Phys. Rev. D 78 (2008)
- E. K. Akhmedov, S. Razzaque, and A. Y. Smirnov, JHEP 1302 (2013)
- PINGU LoI Draft (see P5 SLAC Indico page)

Estimation of NMH Sensitivity

- Results presented here are the product of:
  - Weekly PINGU conference calls for ~2 years (averaging 25 attendees)
  - Half-dozen IceCube meetings and PINGU-specific workshops
  - PINGU LoI (draft copy distributed to P5) is going through standard IceCube paper review process and IceCube Scientific Advisory Committee oversight
- Underlying tools from standard full IceCube simulation, including
  - Honda et al. atmospheric neutrino flux models
  - Widely-used GENIE neutrino generator
  - IceCube state-of-the-art ice modeling
  - GEANT4-based particle interactions
  - Event trigger
- Fogli et al.* convention used throughout: $\Delta m^2 = \left| m_3^2 - \frac{1}{2}\left(m_1^2 + m_2^2\right) \right|$

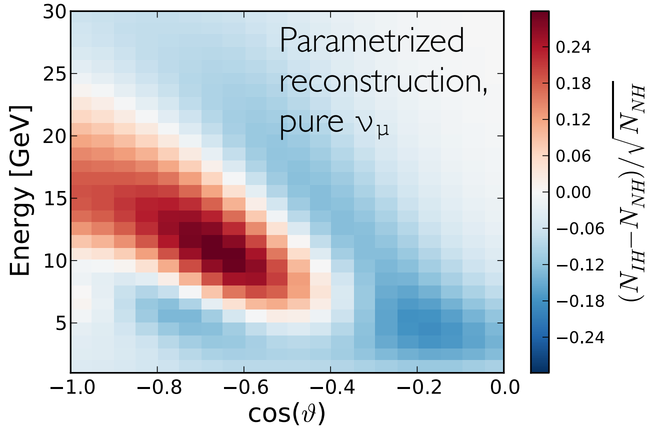
*Prog. Part. Nucl. Phys. 57 (2006)

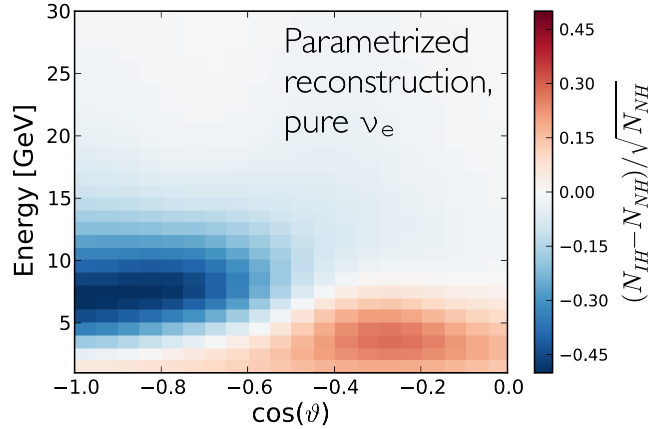
Estimation of NMH Sensitivity

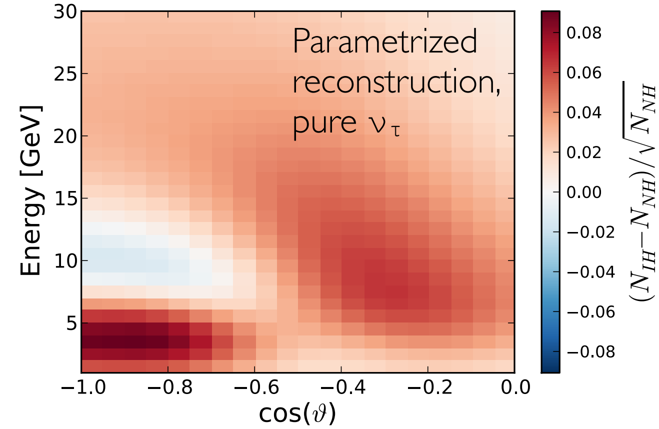
- Event selection and background rejection require
  - Reconstructed event vertex well-contained
  - Reconstructed event direction upward
- Reconstruction
  - Full likelihood minimization in 8-d parameter space (uses "MultiNest")
    - Interaction vertex (x,y,z,t,E), outgoing muon θ, φ, track length
  - Resolutions (improve with energy; given here at $E_{\nu,\,\mathrm{true}} \sim 5$ GeV):
    - $\Delta E/E \sim 0.27$, $\sigma_\theta \sim 13°$ (θ: zenith angle; track & cascade resolutions ~same)
  - Basic track vs. cascade particle ID (improves with energy)
    - 52% of ν_μ (37% of ν_e) (mis-)identified as track-like at ~5 GeV
    - 75% of ν_μ (25% of ν_e) (mis-)identified as track-like at ~10 GeV

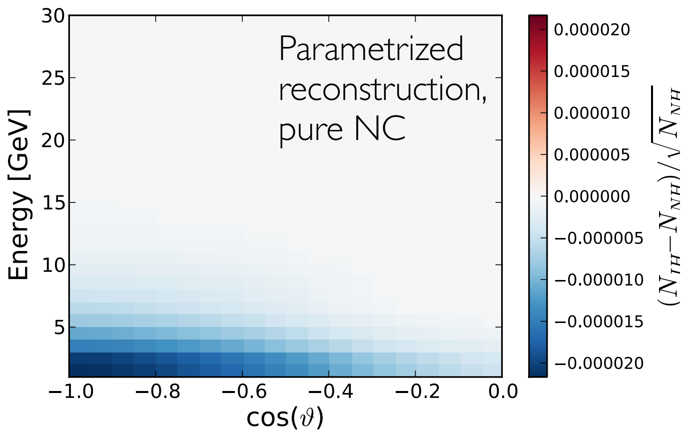
"Distinguishability" Plots*: $(N_{IH} - N_{NH})/\sqrt{N_{NH}}$

Perfect PID for illustrative purposes, no systematics.

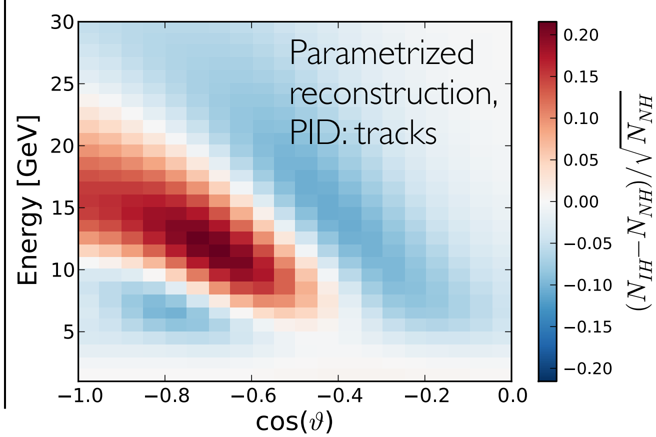


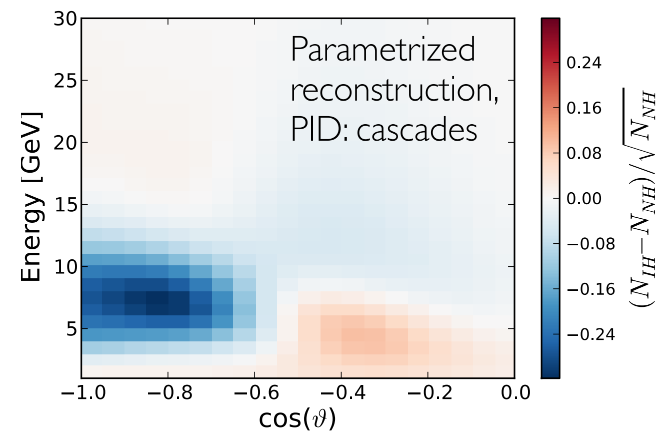






With realistic PID, no systematics.





*As in E. K. Akhmedov et al.

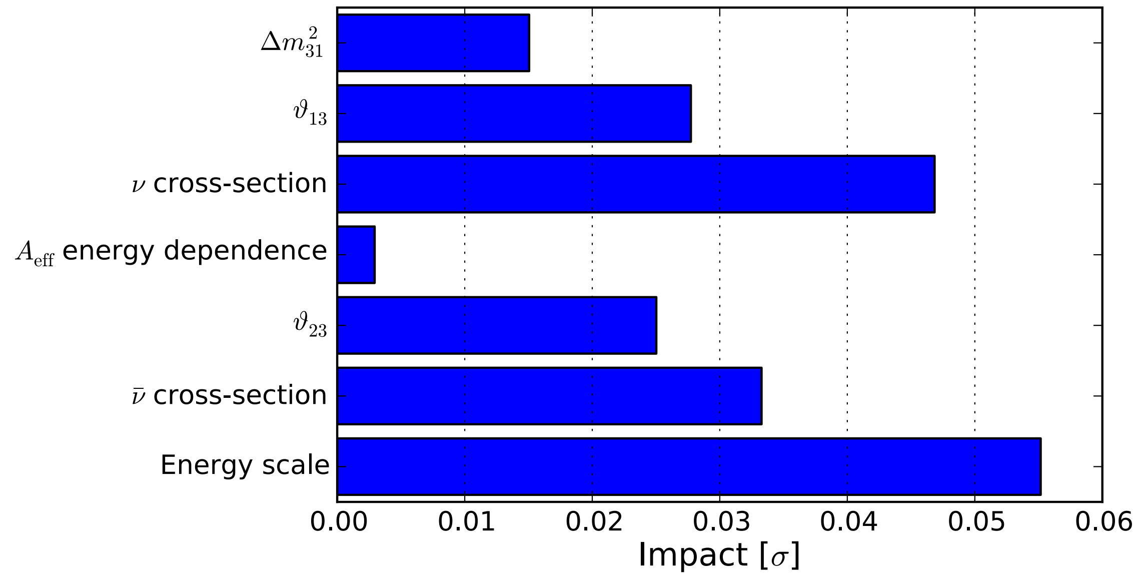
Estimation of NMH Sensitivity

- Three independent analysis techniques
  - “Fisher” approach: detailed detector parametrization, all systematics
    - Quickest evaluation of systematics, new techniques
    - Cross-checked external parametric evaluations of PINGU
    - Verified our implementation of 3-flavor oscillations
  - “Asimov” approach: ave. detector response, full sim., many systematics
    - Relatively fast evaluation using fully simulated data
    - Agrees well with Fisher (within ~5% on final significance)
  - “LLR” approach: log likelihood ratio, full sim., large number of Poisson-fluctuated pseudo datasets
    - Most powerful technique, still under development
    - Time consuming: limited evaluation of systematics presently
    - Agreement with Fisher and Asimov

Systematics: Incorporated via Fisher

Verified with Asimov (all syst.) and LLR (some syst.)

- Apply all systematics
- Un-apply one, "impact" is the observed increase in significance



1. Physics-related

- $\Delta(m_{31})^2$ (prior: $\pm 1\sigma$)*
- θ_{13} ($\pm 1\sigma$)
- θ_{23} ($\pm 1\sigma$)
- cross sections ($\pm 15\%$)
  - ν, anti-ν independently

2. Detector-related

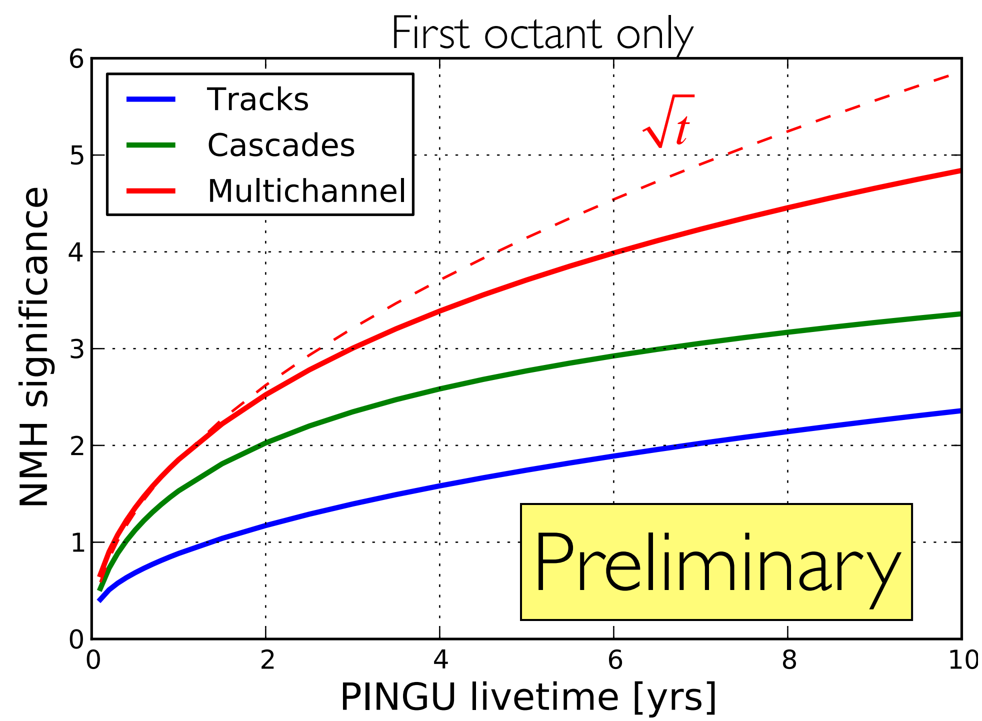
- $A_{\rm eff}(E, \sigma(\nu), \sigma(\text{anti-}\nu))$
- Energy scale ($\pm 5\%$)
- [ice properties]

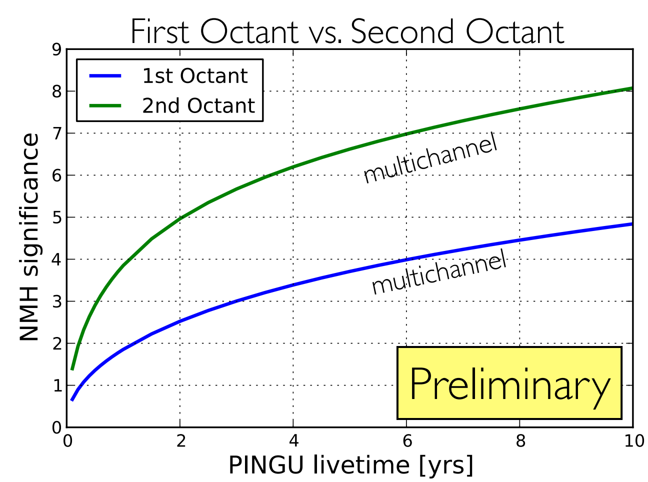
- Other (smaller) errors:
  - $\Delta(m_{21})^2$, θ_{12}, δ_{CP}
  - Scale factors for mis-ID, overall flux normalization

*Prior = $\pm 1\sigma$ error of world ave. msmt.

Result

- Final significance from Fisher analysis
  - Includes all systematics shown plus basic PID
- Significance:
  - 1.85σ in first year of data (first octant)
- Growth in significance as shown
  - Reach 3σ in roughly 3 yrs
  - Livetime from partially built detector not included
- Analysis fully updated since Snowmass
  - Factors lowering significance:
    - higher MC sampling to eliminate unanticipated systematic bias from fluctuations
    - more accurate resolution parametrizations
    - inclusion of NC events
    - kinematic suppression of ν_τ events
  - Factors raising significance:
    - improved event selection
    - improved event fitting
    - use of cascades, PID





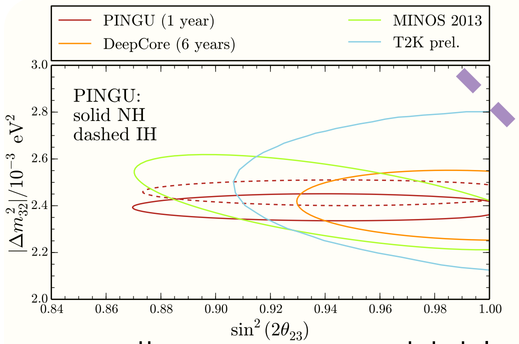
Expected Systematics Mitigation

- Energy scale uncertainty
  - Precision *in-situ* calibration light sources
    - Expect better than 3% calibration of light output (E scale systematic was 5%)
- Ice property uncertainties
  - calibration light sources
- Neutrino, anti-neutrino cross section uncertainties
  - future Minerva results
- Other possible systematics
  - Cascade and track energy resolution uncertainties
    - calibration light sources
  - Cascade directional resolution uncertainty
    - muon-tagged cosmic ray air shower neutrinos

Known Future Enhancements

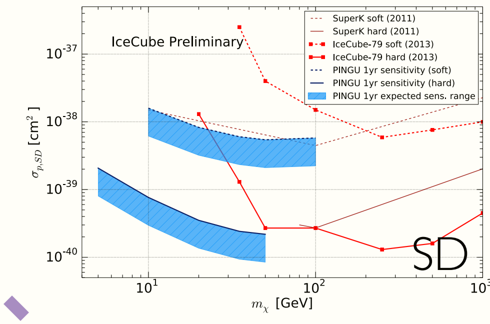
- Geometry optimization (now underway)
  - Initial look at higher density shows promise
  - Studying tradeoff between improved resolution & PID vs. decreased statistics
- Improved particle ID
  - Higher density array does better
- Inelasticity "y"
  - Predict 20-50% significance increase (Ribordy & Smirnov, 1303.0758)
  - Not yet studied for PINGU
- Upgrade fitter (now underway)
  - include separate directions of outgoing lepton and initial vertex
- Use downward contained events for improved normalization
- 10%-scale improvements in acceptances

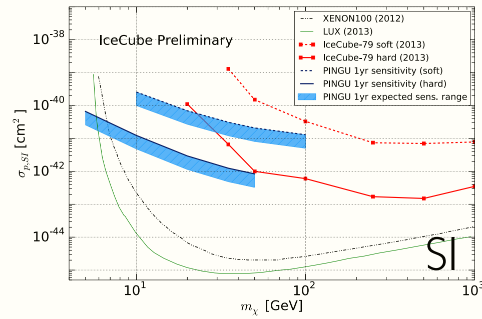
Other Physics Potential of PINGU



ν_μ disappearance: highly competitive after 1 yr

See IceCube result, PRL 111, 081801 (2013)





Indirect WIMP searches: reach M_χ~5 GeV, world-leading limits in SD channel after 1 yr

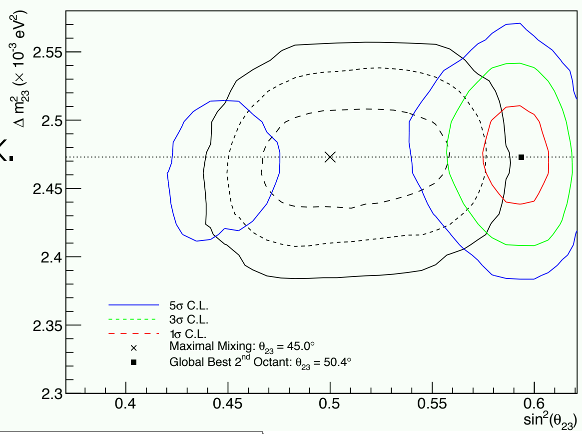
PINGU Livetime (years)

1

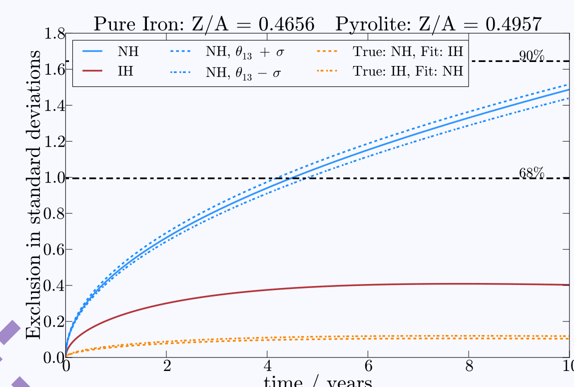
5

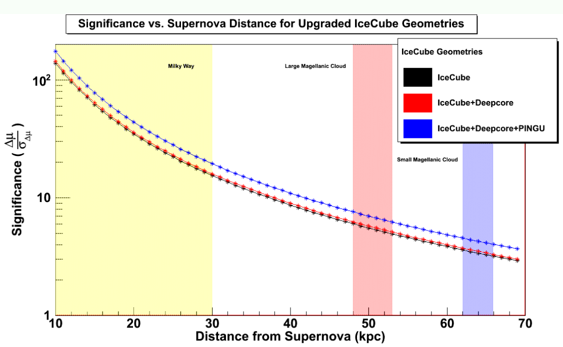
10

Exclude max. mixing @5σ after 5 yrs



Earth tomography: exclude pure Fe core at 90% in ~12 yrs





2x sensitivity to galactic SN (at any time)

Please see LoI for more details!

PINGU Schedule and Budget

- Schedule from funding start
  - 5 years to detector completion
  - 3.5 years to first data
- Funding: NSF PHY/PA, NSF Polar Programs and foreign partners
- Budget
  - For "standalone" PINGU, US cost would be ~$60M
    - $21M fixed costs, $1.61M/string, $25M foreign contribution
  - As part of a "facility" at Pole, US cost would be ~$40M
    - $7M fixed costs, $1.44M/string, $25M foreign contribution
  - 23% contingency not included
  - More details in backup slides

Conclusions

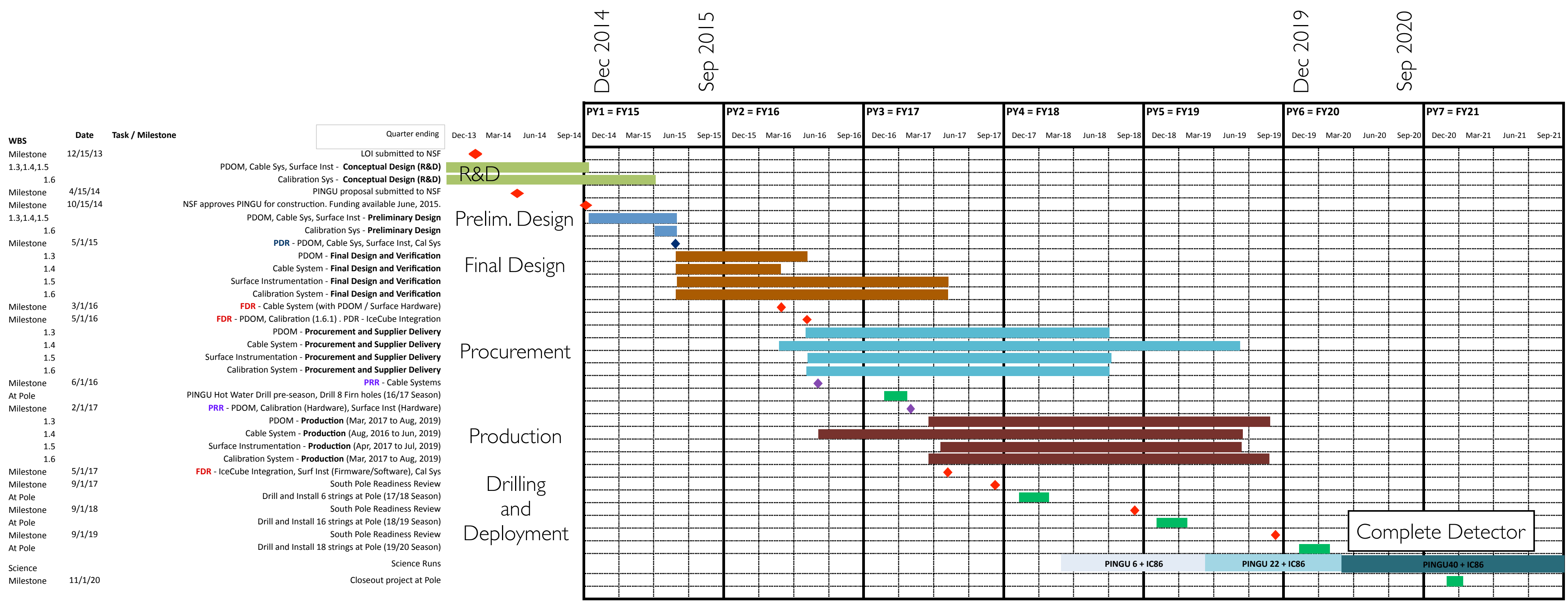
- PINGU can measure the neutrino mass hierarchy
  - 3σ in 3 years
    - have included wide range of systematics
    - still have room to grow the significance
  - measurement complementary to NOvA/LBNE & reactor expts
    - must have combined experiments for 5σ measurement across full δ_{CP} range
    - knowledge of NMH will enhance sensitivity to δ_{CP}
    - NMH is important enough to measure more than once
- PINGU has extensive physics program in addition to NMH
- PINGU can be designed and built quickly with known technology
- PINGU cost is relatively low

Thank you for the opportunity to present PINGU!

Backup slides

PINGU Schedule and Budget

- Based on IceCube experience:
  - 86 strings, ~$278M, 7 years, ~12% non-US
  - On time and on budget.
- Preliminary PINGU schedule shown below
  - ~5 yrs from funding start to detector completion (~3.5 yrs to first data)
  - Here, funding t_0 optimistically defined as fall 2014



PINGU Schedule and Budget

Performed rough top-down estimate first, scaling from IceCube.

Followed with bottoms-up estimate detailed to L3 in WBS. Budgets provided by PINGU L2 leads, all of whom have IceCube experience.

Two numbers came out nearly the same.

PRELIMINARY	Item	PINGU Alone	PINGU as part of IceCube Facility*
Fixed Costs	PINGU Project	20.6	7.0
Per-String Costs	PINGU Project	46.9/40=1.17	41.3/40=1.03
	Polar Support	17.4/40=0.44	16.45/40=0.41
	Total	1.61	1.44
Non-US Contribution	Total	25	25
Net US Cost	Total w/o Contingency	20.6+(1.61*40)-25= **$59.9M**	7.0+(1.44*40)-25= **$39.7M**
	Total w/Contingency (~23%)	25.5+(1.99*40)-25= **$80.1M**	8.7+(1.77*40)-25= **$54.6M**

*__Facility__: HE Extension, PINGU, surface array (plus ARA? DM-Ice?), all can leverage IceCube presence and experience. Savings accrue from shared resources: drill, cable/PDOM devel., Mgmt., IC Integ., ICL upgrade...

Bottoms Up Budget Estimate

PINGU Alone (not part of a Facility)

WBS	Name	Labor	Capital Equipment	Materials & Supplies	Travel	Services	Total without contingency	L2 Contingency % based on Risk Factor	TPC with contingency
1.1	Project Office	$5,099,338	$0	$458,850	$463,975	$320,233	$6,342,396	16%	$7,357,180
1.2	Drilling	$6,799,359	$3,715,000	$475,000	$754,148	$0	$11,743,507	28%	$15,031,689
1.3	PDOM	$5,211,793	$13,637,500	$614,000	$212,269	$20,000	$19,695,562	25%	$24,619,453
1.4	Cable System	$2,389,101	$9,363,800	$445,000	$137,023	$500,000	$12,834,924	25%	$16,043,655
1.5	Surface Instrumentation	$2,758,162	$294,000	$136,000	$180,667	$10,000	$3,378,829	25%	$4,223,536
1.6	Calibration System	$3,408,537	$165,000	$125,000	$237,082	$0	$3,935,619	22%	$4,801,455
1.7	IceCube Integration	$4,199,887	$1,230,000	$192,000	$280,991	$0	$5,902,878	16%	$6,847,339
1.8	Polar Operations (except drilling)	$3,000,398	$180,000	$154,000	$218,743	$85,000	$3,638,142	16%	$4,220,245
1.9	Antarctic Support Contractor (ASC)	$0	$0	$0	$0	$17,359,600	$17,359,600	22%	$21,178,712
	Totals	$32,866,575	$28,585,300	$2,599,850	$2,484,899	$18,294,833	$84,831,457	23.0%	$104,323,262

Subtract $25M non-US contribution

PINGU Cost Profile

Cost/year ($M)							
	2014	2015	2016	2017	2018	2019	Total
PINGU "Alone" (not part of a Facility)							
No Contingency (add 23%)	4.3	15.6	30.6	16.0	16.2	2.0	84.8
PINGU as part of a Facility							
No Contingency (add 23%)	3.3	11.9	23.2	12.1	12.3	1.5	64.3

Notes:

No foreign contributions included. Subtract ~$25M from totals.

Approximated "Facility" cost profile by scaling "PINGU Alone" costs by (64.3/84.8).

Breakdown: Possible Foreign Contributions

- Germany: $7M capital equipment, $3M personnel (DESY + Institutions)
- Canada: $7.7M from CFI request
- Japan: $1M
- South Korea: $5.5M for new IBS 'Center for Neutrino Astroparticle Physics' at SKKU
- Denmark: $680K from Carlsberg Foundation
- Belgium: $650K
- UK: exploratory phase
  - have "Newton" fellow postdoc on PINGU now
- Sweden: exploratory phase

Total non-US: ~$25M

Non-US R&D funds may become available in the near term, with full funding contingent on US approval.

Basis of Estimate Summary: PINGU Alone

- WBS 1.1: Project Office
  - Detailed backup in WIPAC budget template format including job titles, travel, M&S
  - 7% of TPC compared to 7.2% actual from IceCube
- WBS 1.2: Drilling
  - Detailed PINGU drilling presentation given at IceCube May, 2013 Collaboration Meeting (Benson, Cherwinka, Hutchings, Haugen)
  - 14.2% TPC compared to 14.3 % for IceCube
- WBS 1.3: PDOM
  - All major components have re-quotes that are one year or less old (PMT, sphere, HV generator, HV base, HV control, penetrator assembly, etc. – $13.6M of $19.7M total)
  - Integration / Test section (mostly labor + M&S) based on 3500 IceCube DOMs produced at PSL
  - Continuous production from March, 2017 to Aug, 2019
- WBS 1.4: Cable Systems
  - Carried over actual cable costs from IceCube which included raw cable from Ericsson and breakout production at Seacon
  - Labor estimate also based on IceCube actuals. Continuous production for 3 years (Aug, 2016 to June, 2019)
  - Highest risk item, from budget, standpoint is the estimate for the work to be done at the ICL to accommodate 40 new strings (current estimate at $1.2M)

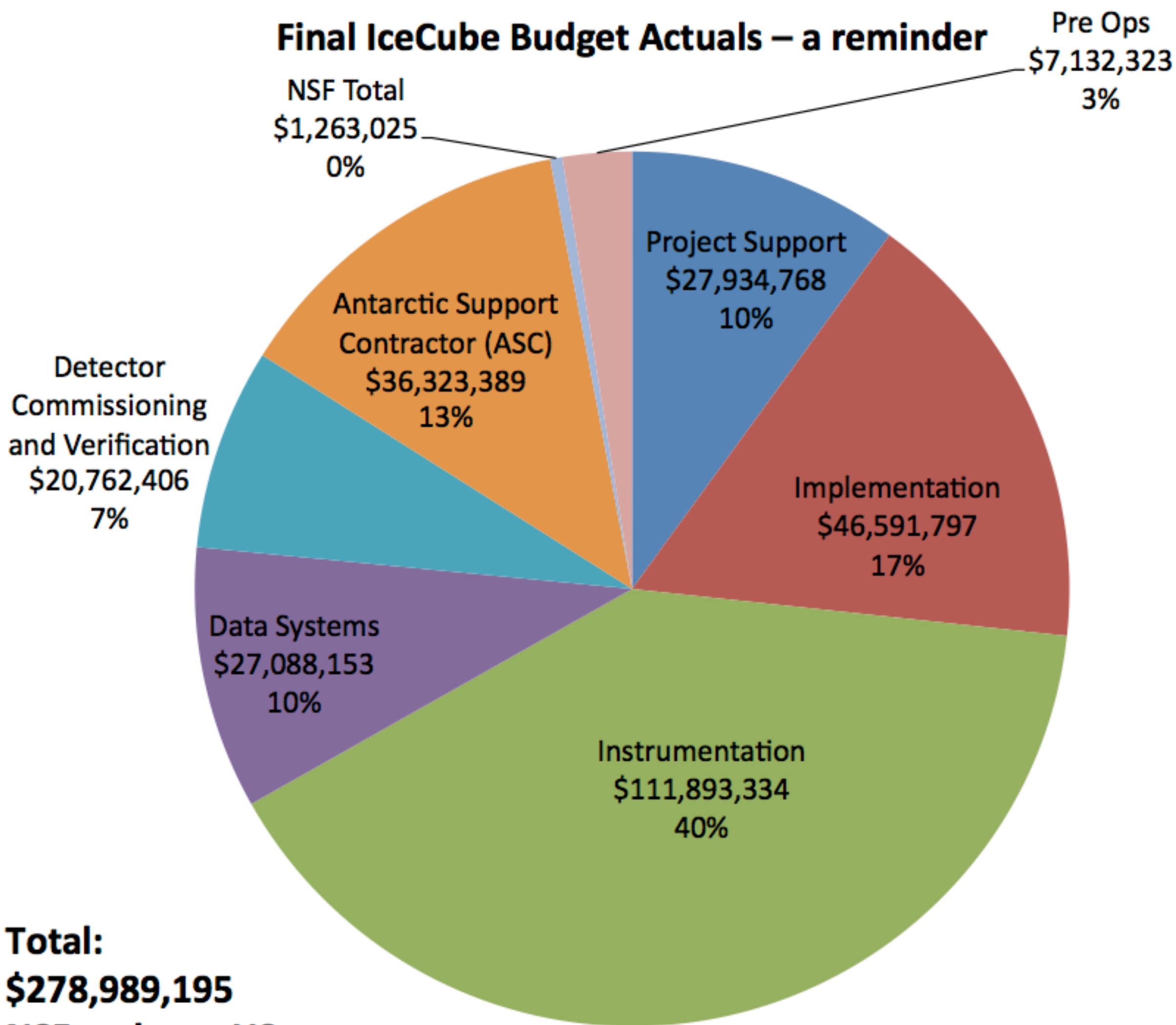
Basis of Estimate Summary: PINGU Alone

- WBS 1.5: Surface Instrumentation
  - Estimate supplied by Kael Hanson, one of the IceCube DAQ leads
  - $5600 / channel Cap Equip costs
- WBS 1.6: Calibration System
  - Vetted by Chris Wendt and Dawn Williams, IceCube calibration leads
  - Comparatively high labor content as a result of meeting new technical requirements
- WBS 1.7: IceCube Integration
  - Detailed bottoms up by IceCube Computing Lead
  - Several conference calls with current IceCube experts across IceCube online/offline systems
- WBS 1.8: Polar Operations
  - This is mostly labor and travel to Pole
  - Puts 14 people on the ice to do everything other than drilling. This compares to 20 for IceCube actual construction years which also included IceTop
- WBS 1.9: Antarctic Support Contractor
  - Based on IceCube actuals with following adjustments:
    - No IceTop
    - No 'new' ICL
    - Fuel at $29 / gallon
  - Higher % than IceCube because of fuel costs ($11 vs $29)

Basis of Estimate: PINGU as part of Facility

- Adjust each Level 2 WBS element while considering above question
  - 1.1: (Project Office) PINGU will take 80% of Project Support during 3 main PINGU deployment years
  - 1.2: (Drilling) PINGU only pays for drill meeting new requirements. Facility bears brunt of refurbishment. Only pay for drilling years.
  - 1.3: (PDOM) Facility pays for Design / Verification cycle. PINGU pays for Cap. Eq. and Labor during main production years
  - 1.4: (Cable) Same as 1.3 except take away ICL upgrade to accommodate 40 cables
  - 1.5: (Surface Instrumentation) Keep all Cap Eq but share labor at 50% with Facility
  - 1.6: (Calibration) Keep all Cap Eq but share labor at 80% with Facility
  - 1.7: (Integration) Assume 50% of labor to be carried by Facility
  - 1.8: (Polar Ops.) Only budget for 3 main deployment years
  - 1.9: (ASC) Only budget for 3 main deployment years

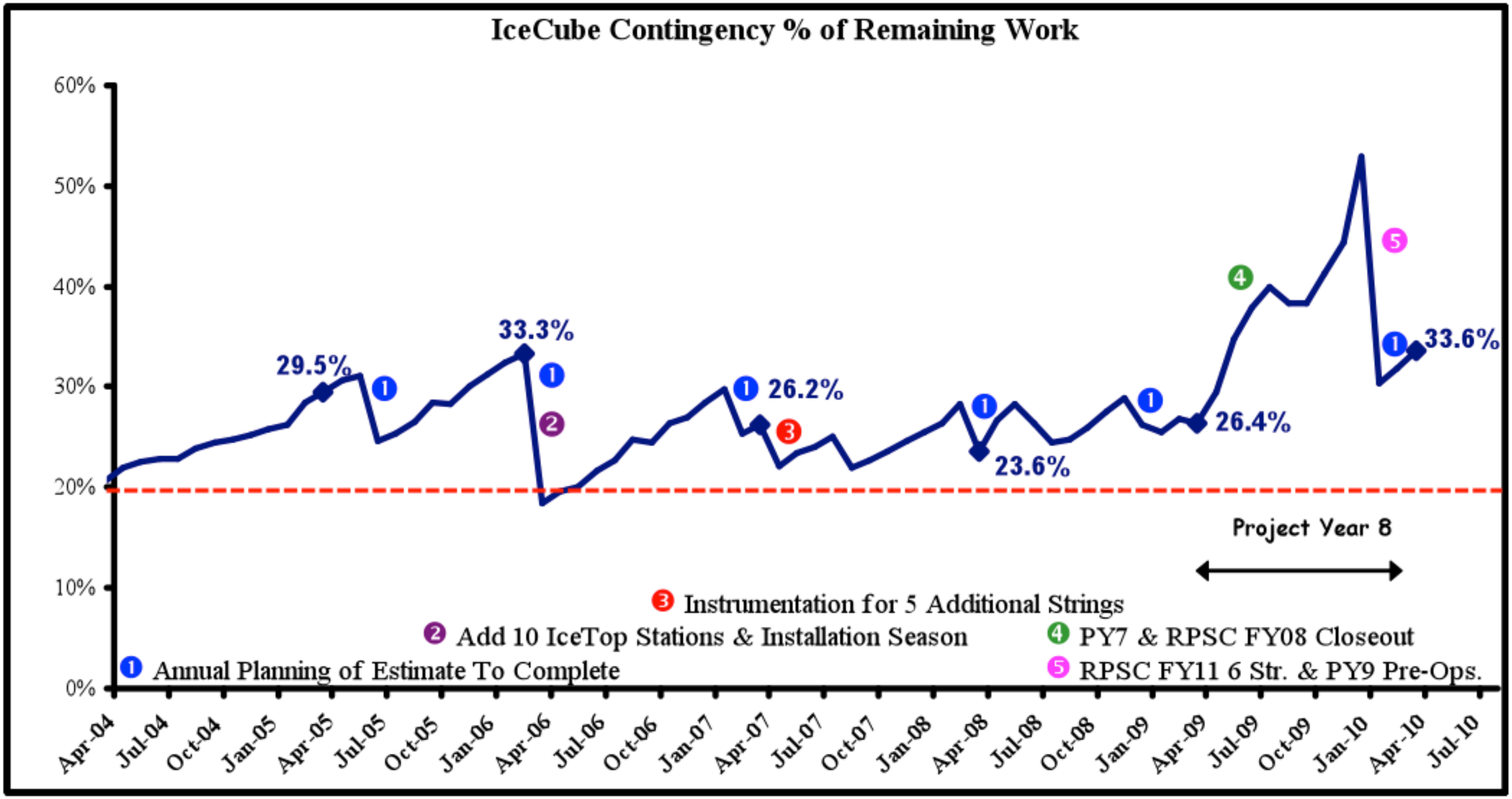
IceCube Final Budget



Total:
$278,989,195
NSF and non-US

IceCube Contingency Experience

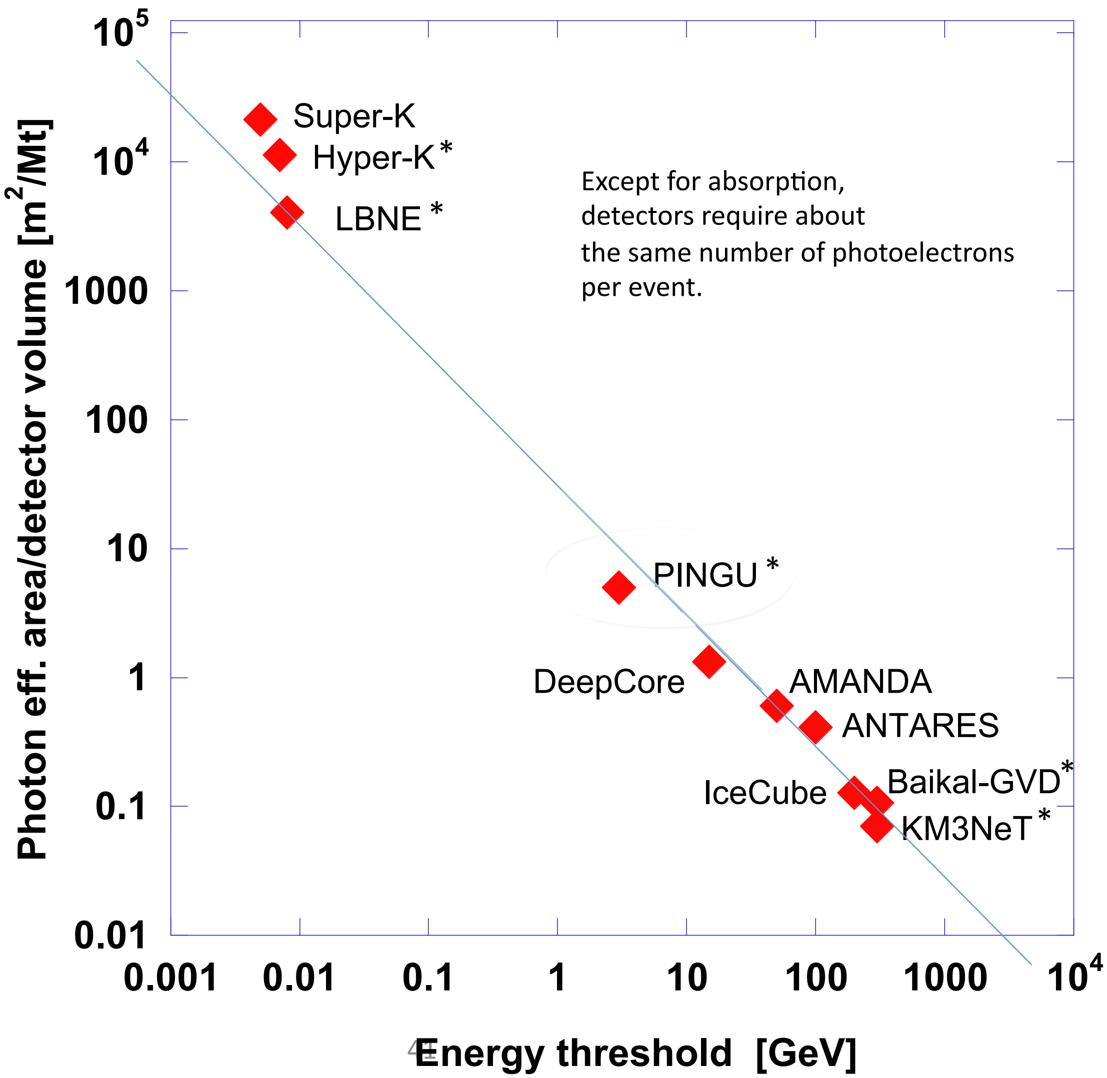
April 2004 – March 2010



Budget Notes

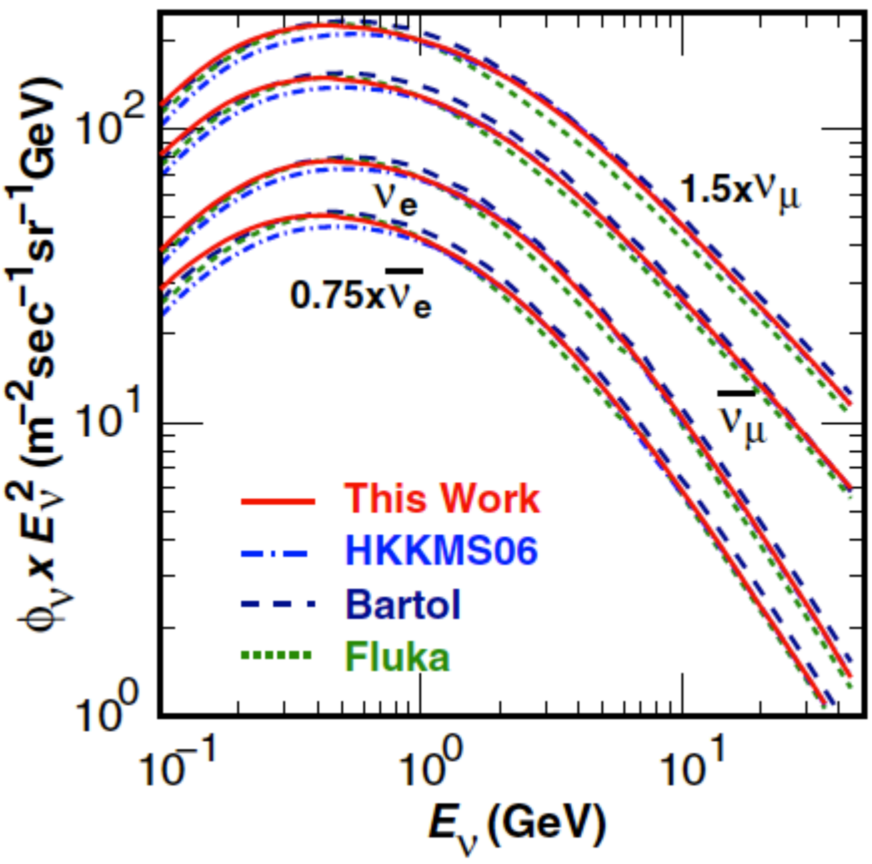
- Why PINGU cost is less than (40/86)*270M=$126M:
  - no IceTop
  - no drill design
  - lower pre-ops

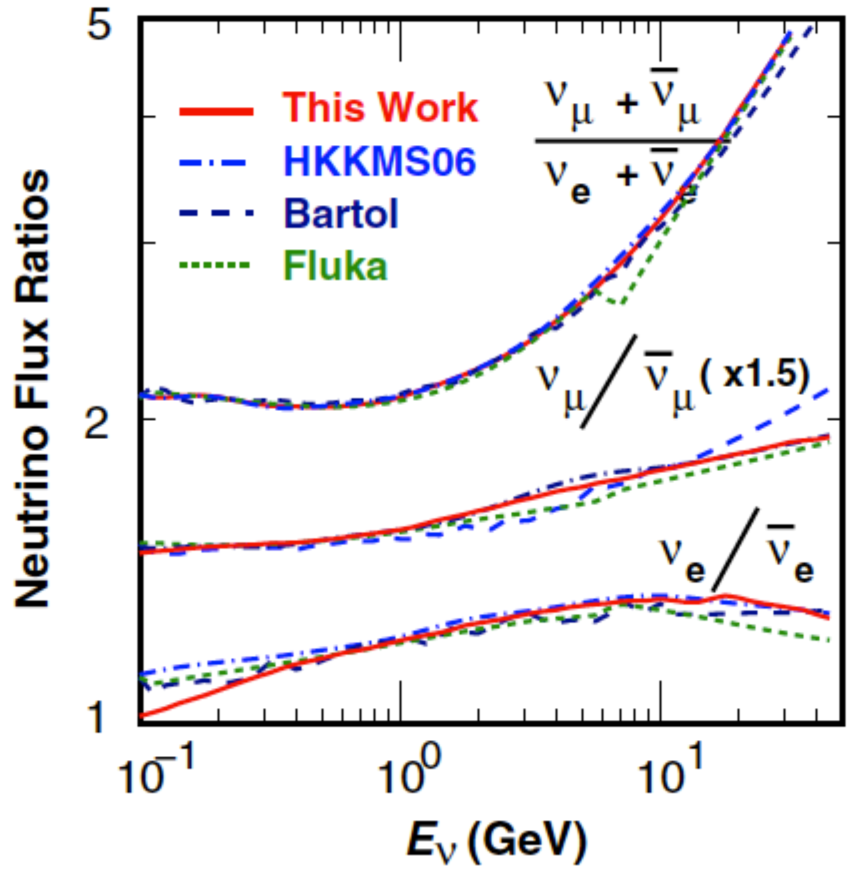
Neutrino Detectors: Optical Water Cherenkov



- Definitions:
  - Photon effective area $= N_{PMT} \times Area \times QE$ = equivalent area of 100% photon detection
    - collection eff. not included
  - Asterisks indicate design study
- Photon effective area goes as $\sim 1/E_{thr}$

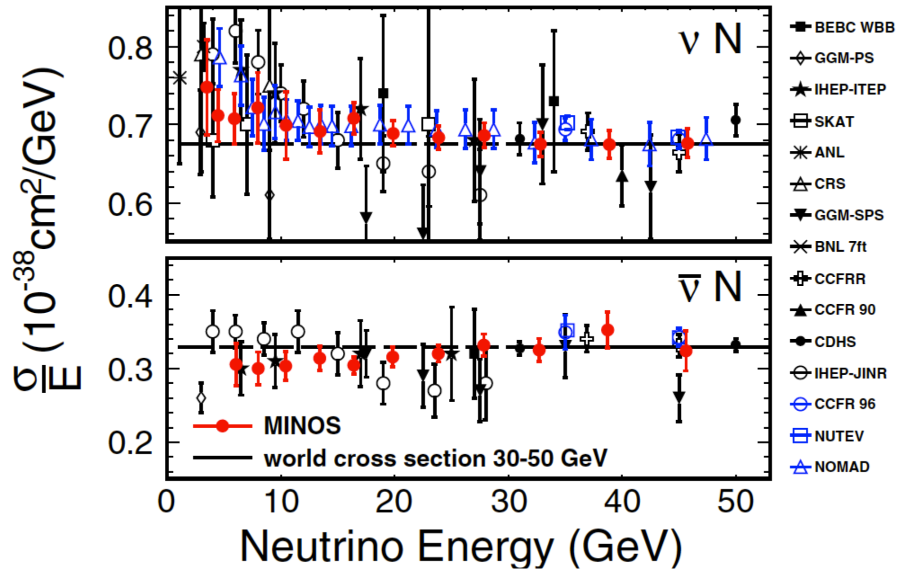
Atmospheric Neutrino Fluxes



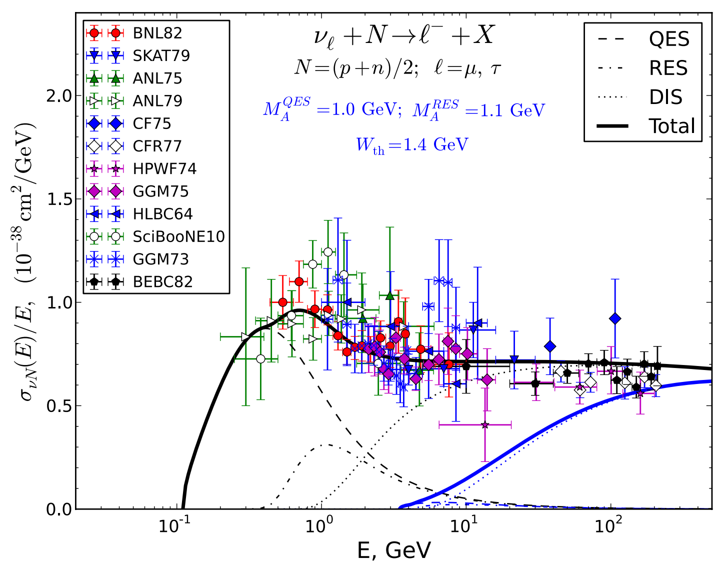


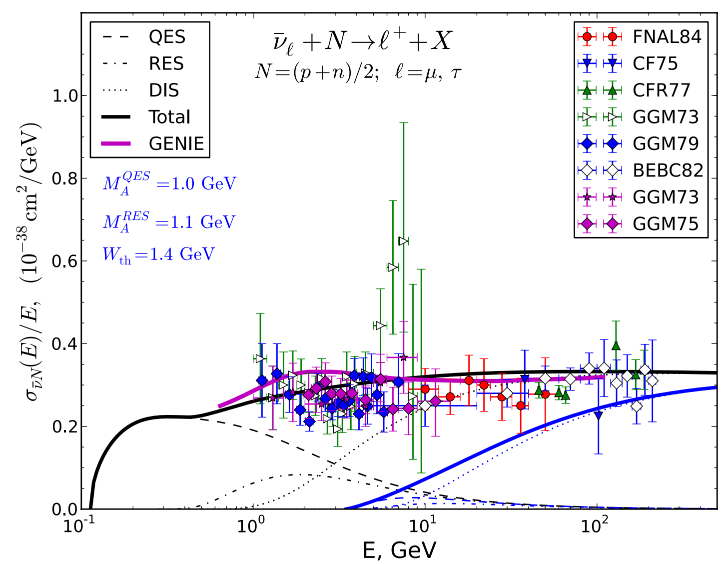
Honda et al., PRD 83,123001 (2011)

Neutrino Cross Sections



P.Adamson et al., PRD 81 072002 (2010)





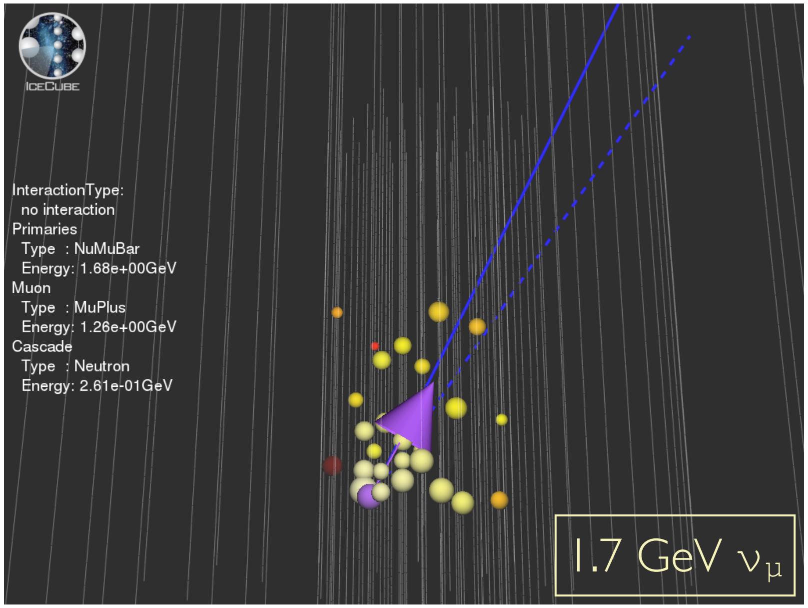
M. Kowalski et al., in preparation

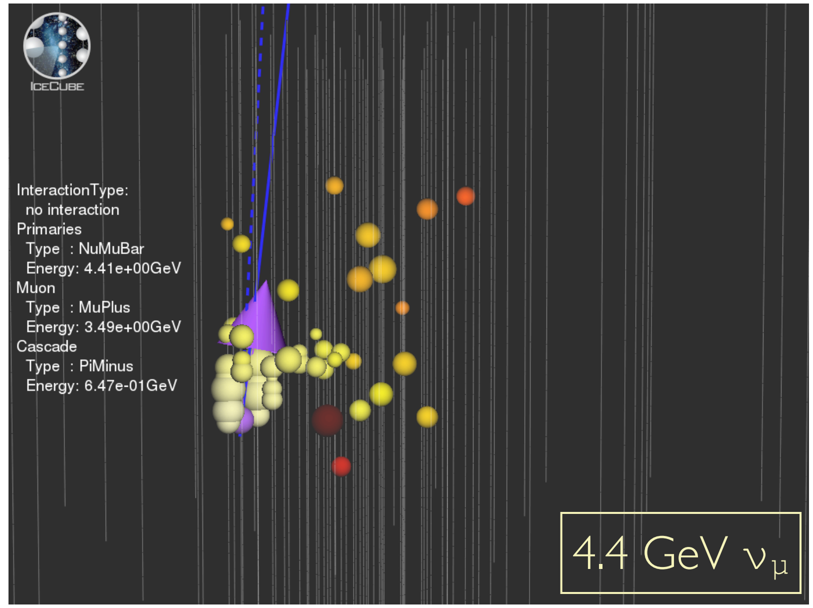
Formaggio & Zeller 1305.7513; GENIE: Nucl. Instrum. Meth. A614: 87-104, 2010

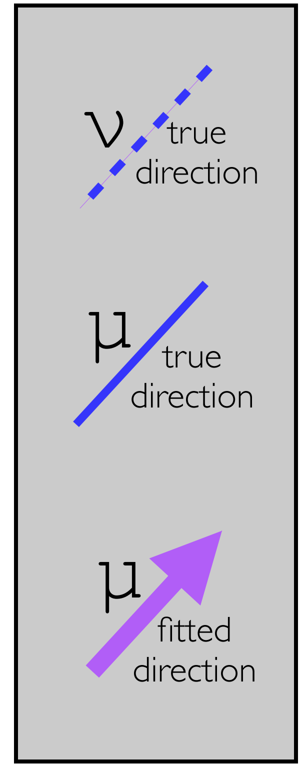
Event Selection

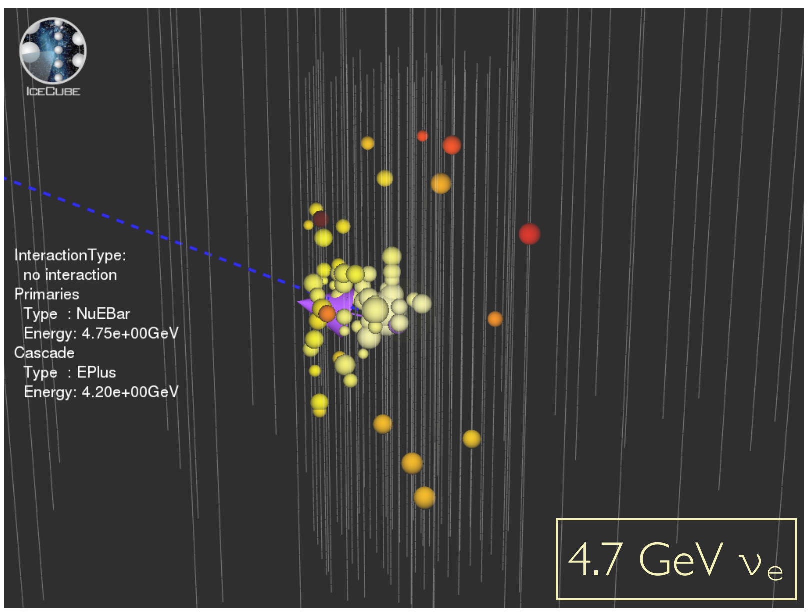
- All using reconstructed variables
- Criteria:
  - Successful reconstruction
    - Currently ~90% efficient (fitter does not converge)
    - Can be improved
  - Containment of reconstructed vertex:
    - $-180 < z < -500$m (some "cushion" top & bottom)
      - Detector center is at $z = -325$m
    - $r < 75$m (relative to central axis)
  - Upward reconstructed direction:
    - $\theta > 90°$
    - This removes ~all downward-going atmospheric muons (background) *and* downward-going atmospheric neutrinos (could provide additional normalization for signal)

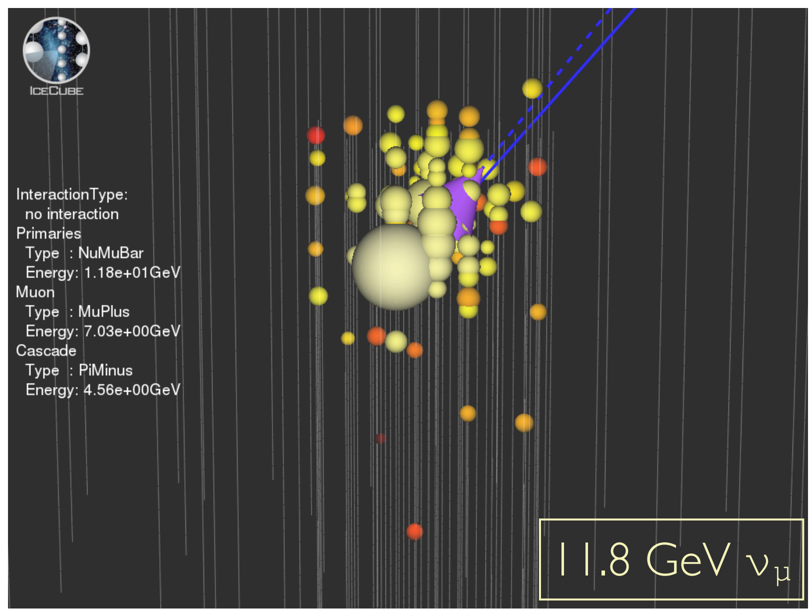
Sample Reconstructed Events







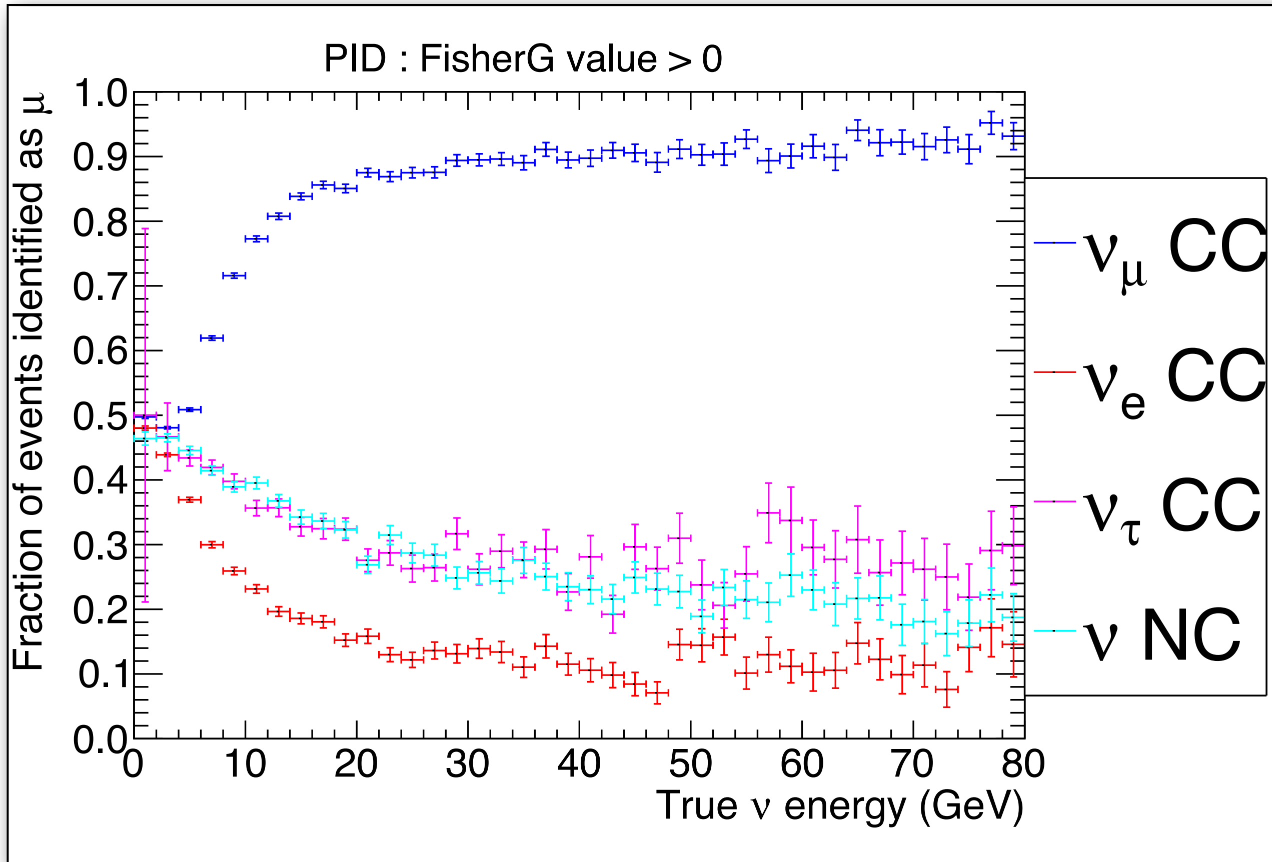




Size of circles: N_γ.
Color: t_γ.

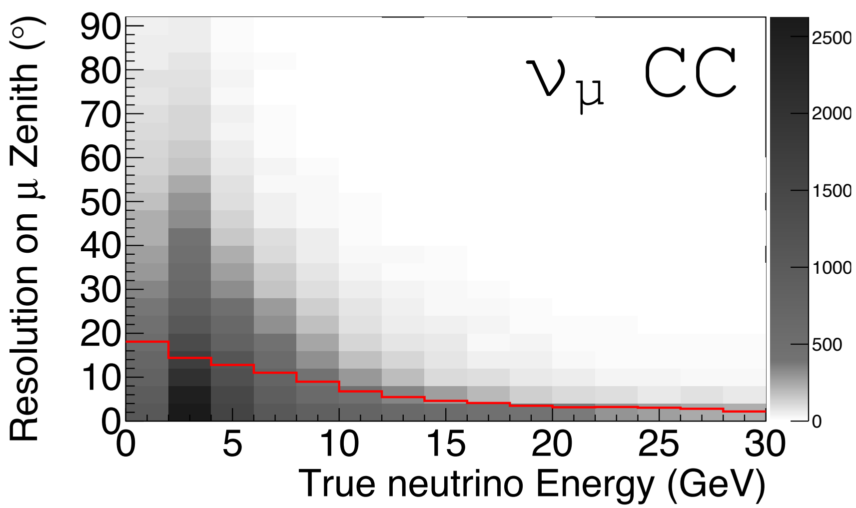
Particle ID

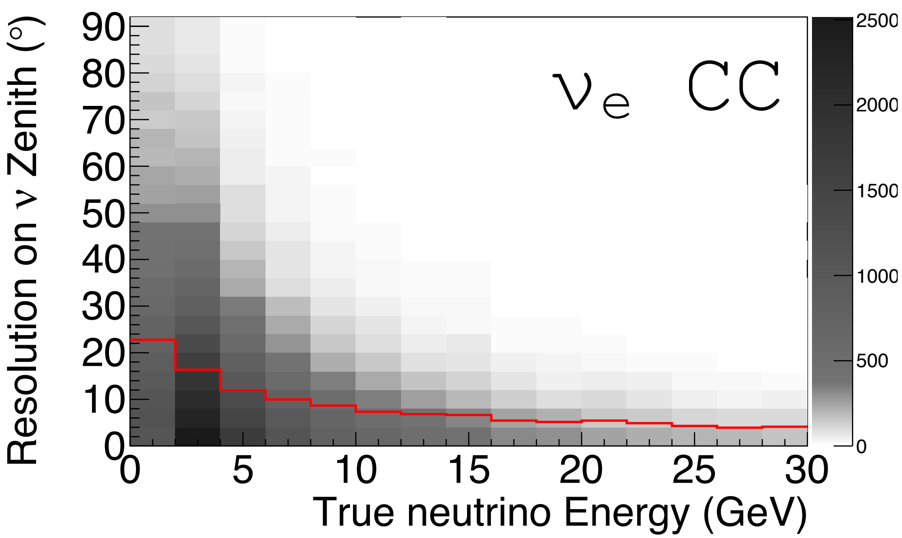
- Need to distinguish track-like from cascade-like events
  - Even basic PID improves significance
- Using these variables:
  - reconstructed track length
  - presence of "early" hits relative to initial vertex
  - ratio of track and cascade fit probabilities



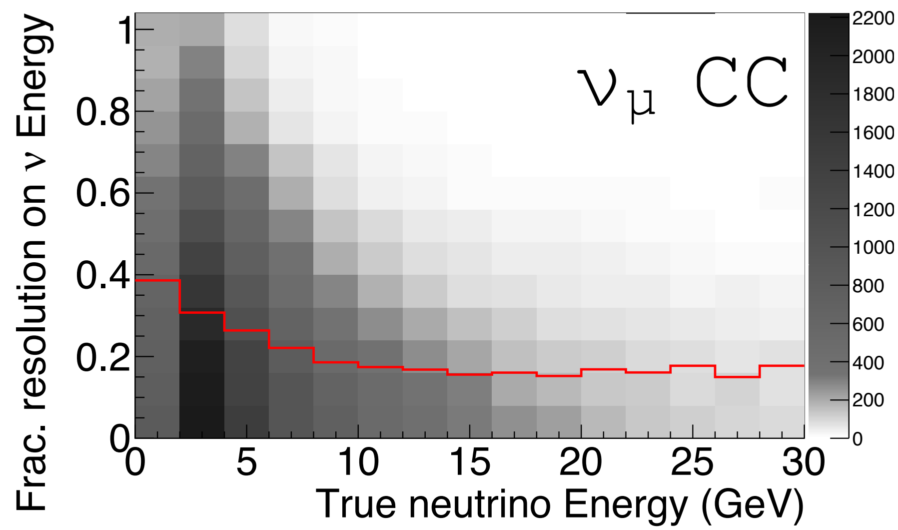
Event Reconstruction Resolutions

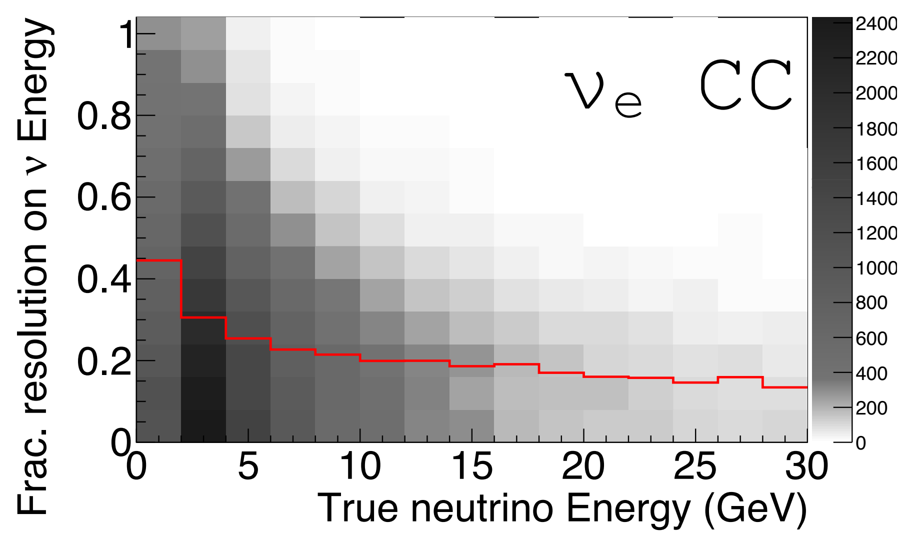
Zenith Angle Resolutions





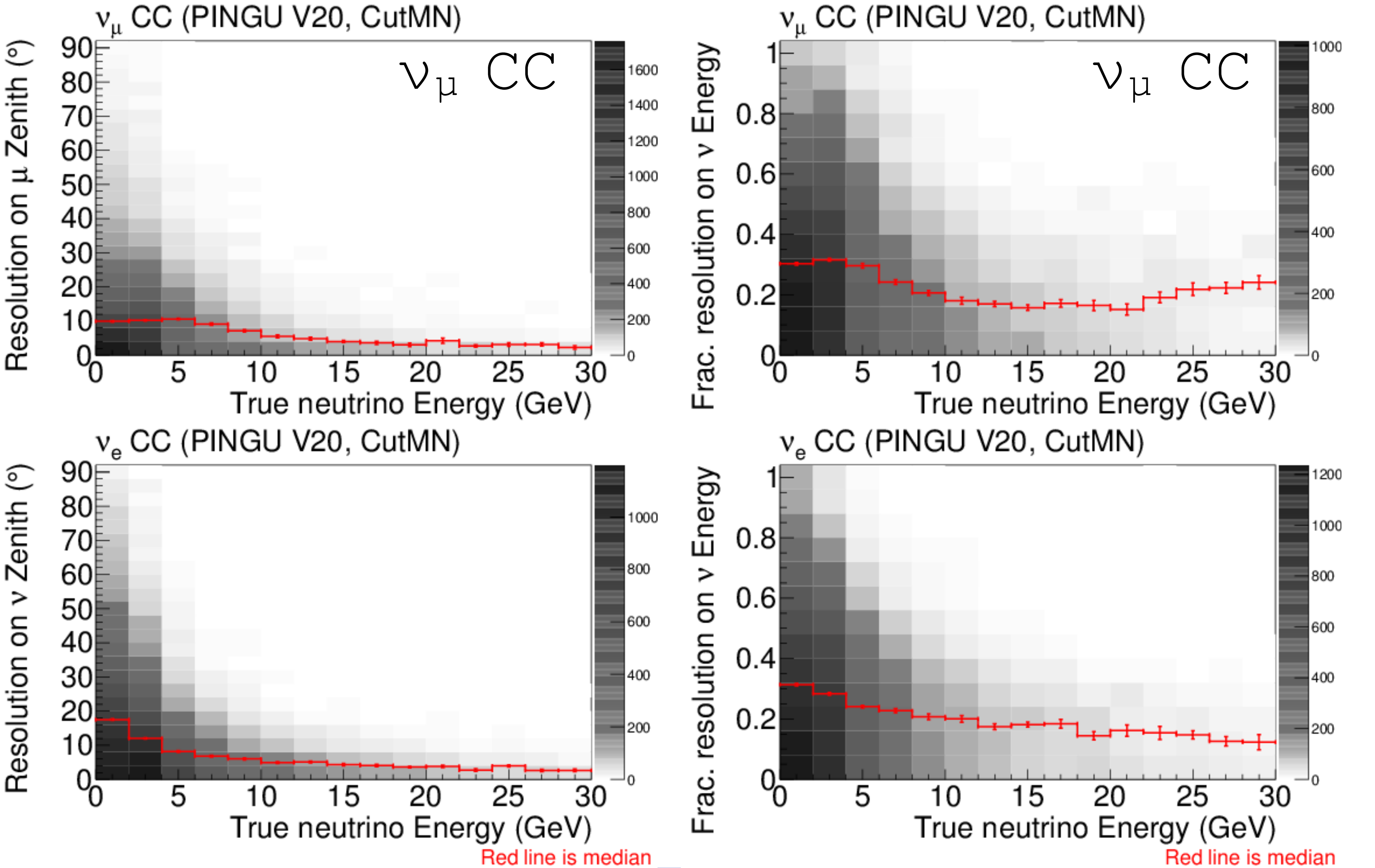
Fractional Energy Resolutions





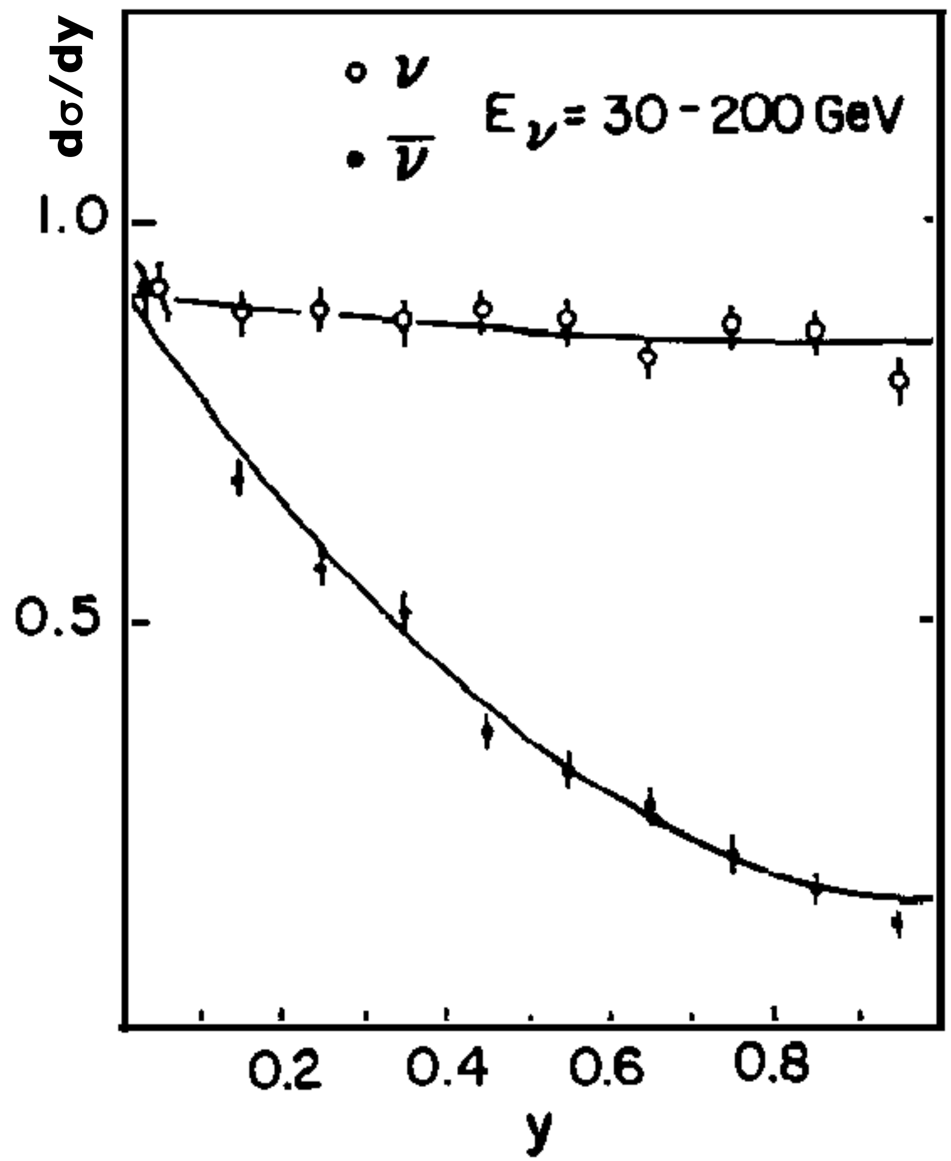
Resolutions: Denser Geometry

Zenith Angle Resolutions | Fractional Energy Resolutions



Inelasticity

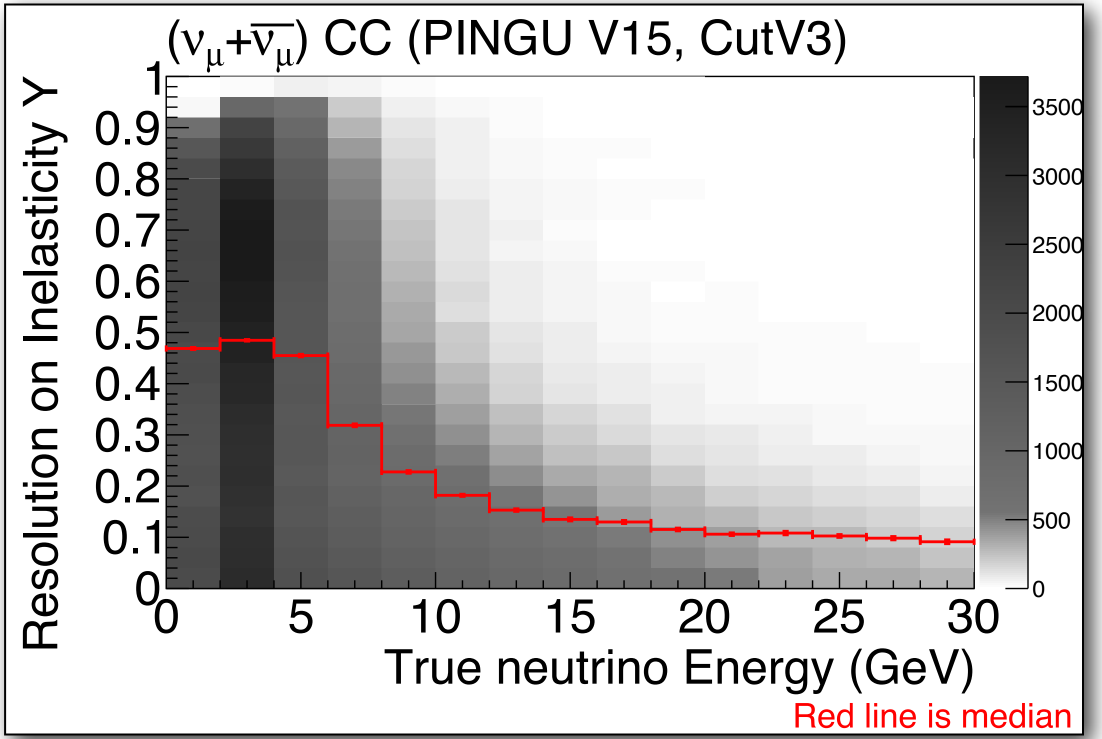
- Inelasticity distribution is different for neutrinos and anti-neutrinos
- Inclusion of inelasticity in the NMH analysis could improve significance by 20-50% (Ribordy and Smirnov, 1303.0758)

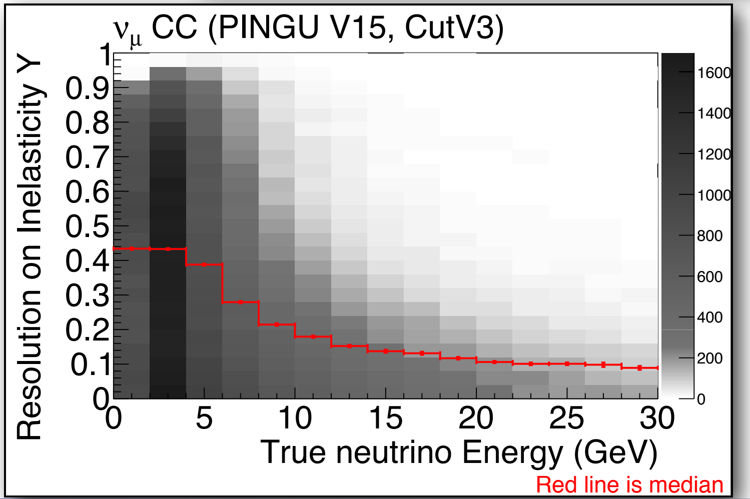


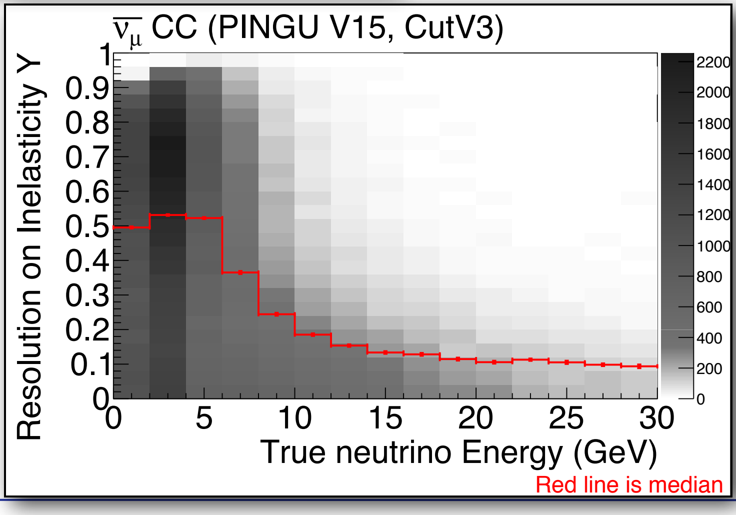
de Groot et al., Z. Phys. C1, 143 (1979)

PINGU Inelasticity Resolutions

Plotted:
$(y_{reco}-y_{true})$
vs.
E_ν



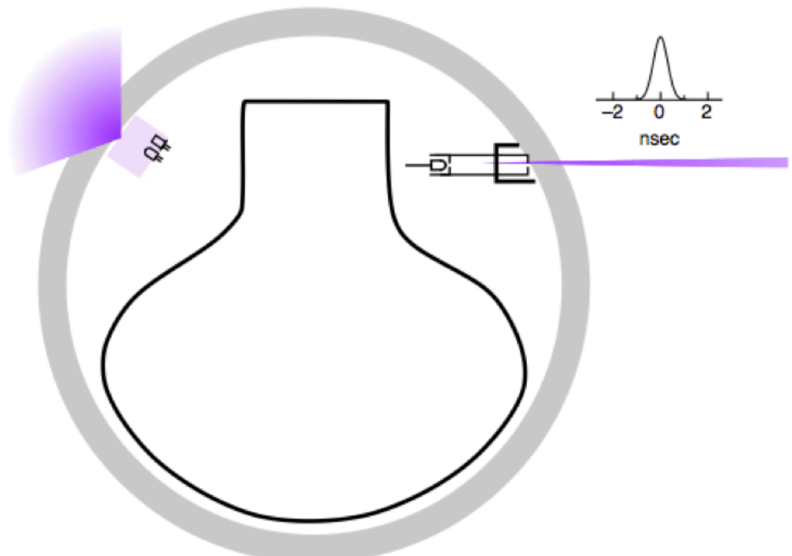




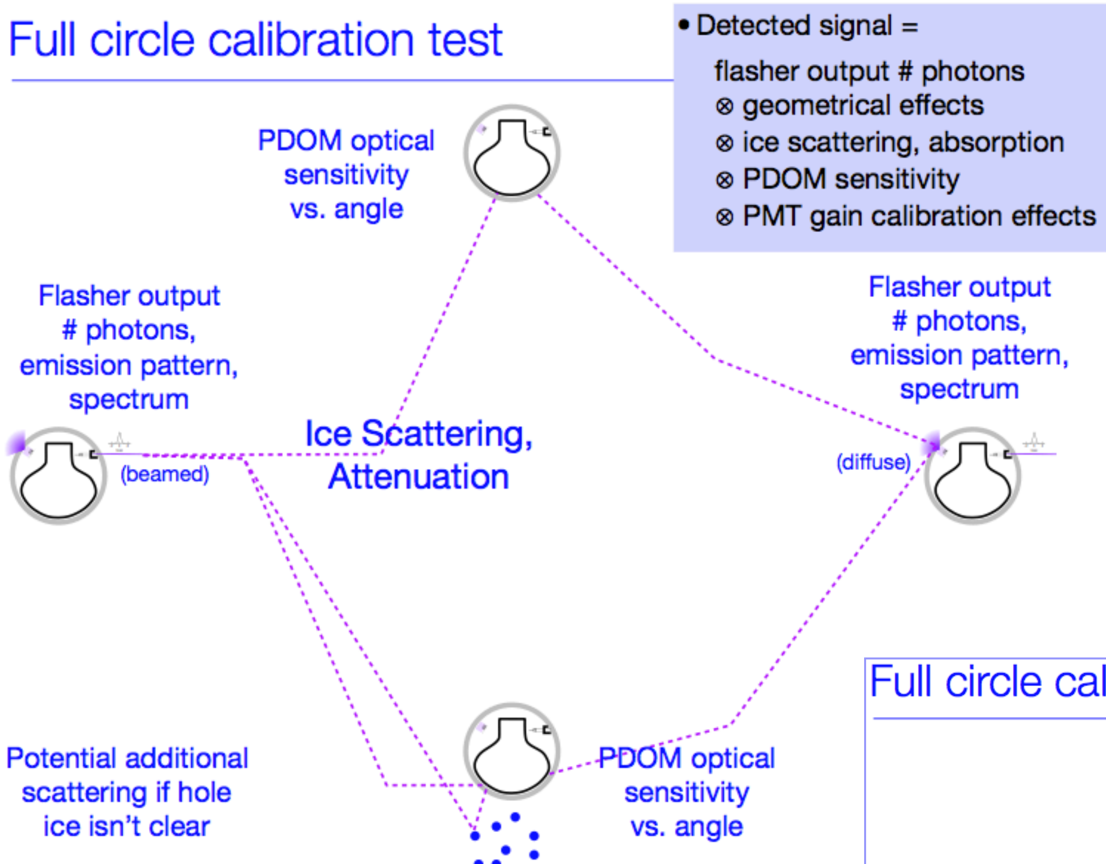
PINGU Calibration

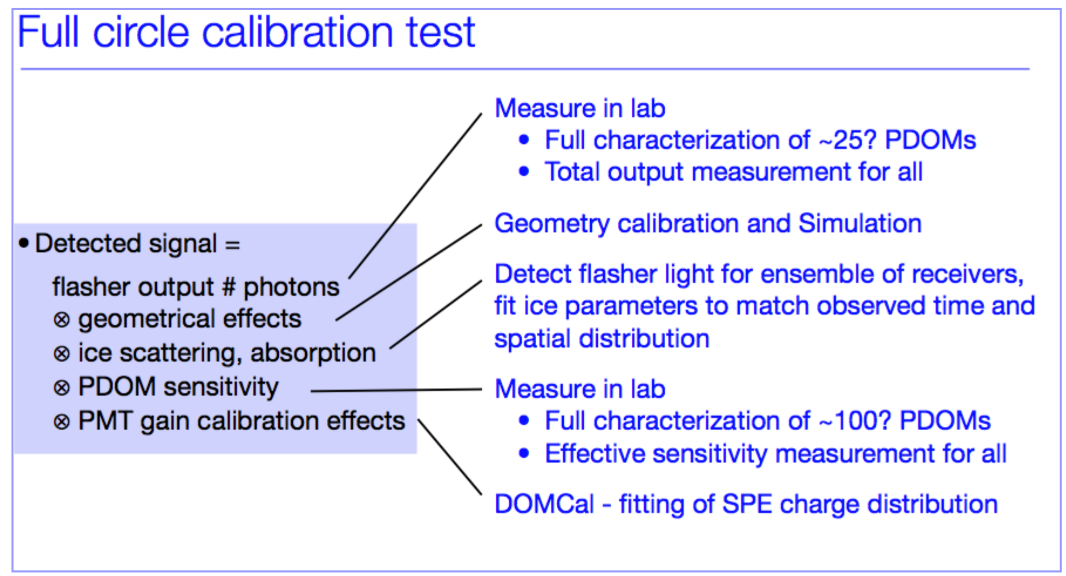
PINGU Flasher LEDs

- Planned improvements over IceCube design
    - ~2 ns pulses
    - Diffuse and narrow beam sources
    - Calibration of light output to within 3%
    - Direction of LED known to within 1°



PINGU Calibration





Fisher Information Matrix

- (Fisher) Information matrix = inverse of covariance matrix
  ➔ full information of all errors and correlations
  ➔ easy implementation of (gaussian) priors

- Construction of the Information Matrix

observables

$$\mathcal{F}_{ij} = \sum_n \frac{1}{\sigma_n^2} \frac{\partial f_n}{\partial p_i} \frac{\partial f_n}{\partial p_j}\bigg|_{\text{fid. model}}$$

measurement error parameters

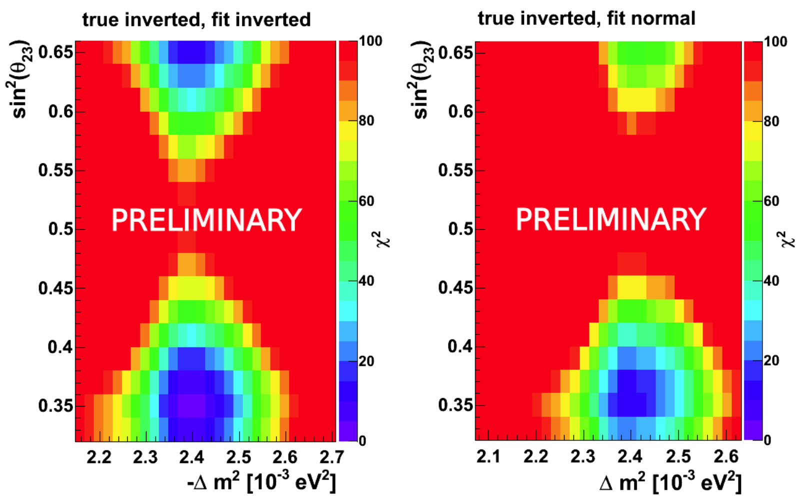
  ➔ valid within gaussian limit of fiducial model

- Implementation for NMH
  ➔ hierarchy parameter: $P(h) = hP_{NH} = (1-h)P_{IH}$
  ➔ physics (Δm_{31}, θ_{23}, …) and detector parameters (A_{eff}, σ_{reco},…)

- Total error on hierarchy parameter yields significance (marginalized over other parameters it is correlated with)

Asimov Data Set

- Steps:
  - Define χ^2 as function of oscillation parameters
  - Handle systematics via pull method (Fogli et al. 0206162v1)
  - Treat Δm^2 as a signed quantity
  - Define $\Delta\chi^2 = \min\chi^2(\mathrm{NH}) - \min\chi^2(\mathrm{IH})$ as test statistic for NMH
  - Apply analysis to representative "Asimov" dataset
  - Significance for Asimov dataset approximates median significance
- With true osc. params -2.4e-3 eV^2 and $\sin^2(\theta_{23})=0.35$
  - estimate number of events in bins of (E,cosθ)
  - minimize χ^2 as a function of oscillation params for each hierarchy
  - take $(\Delta\chi^2)^{0.5}$ as significance

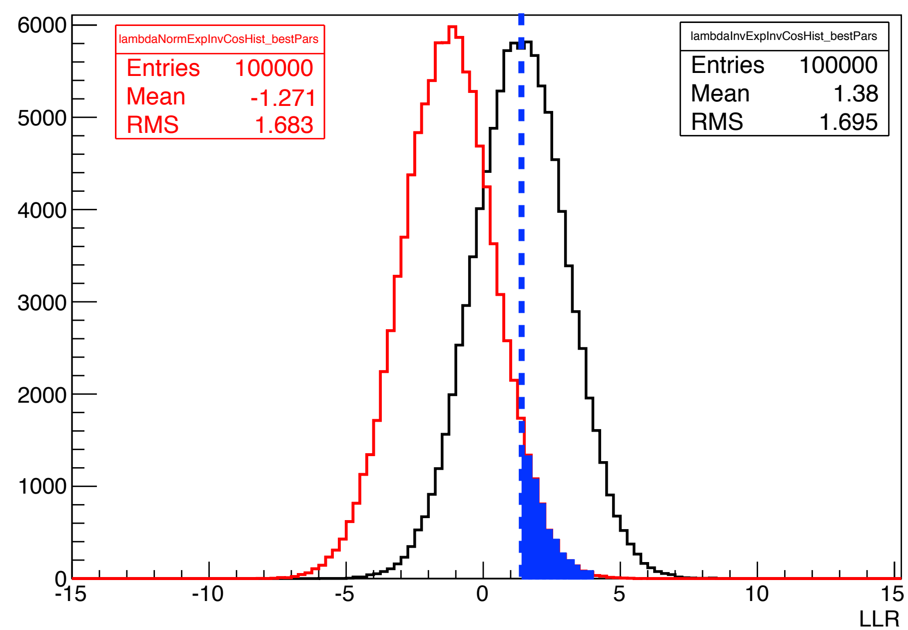


Log Likelihood Ratio

- Generate templates for all oscillation/systematic parameters and hierarchies
- Create pseudo-dataset by pulling from the template and adding Poissonian fluctuations
- Calculate the likelihood of the pseudo-dataset using ALL templates
- Use the best likelihood to determine the LLR, and repeat many times
- Determine the proportion of the distribution which lies beyond the median point in the opposite distribution, giving the p-value for this test

$$LLR = \frac{\sum_{N=0}^{N_{bins}} \mathcal{L}(Data_{NH}|Template_{IH})}{\sum_{N=0}^{N_{bins}} \mathcal{L}(Data_{NH}|Template_{NH})}$$

$$LLR = \frac{\sum_{N=0}^{N_{bins}} \mathcal{L}(Data_{IH}|Template_{IH})}{\sum_{N=0}^{N_{bins}} \mathcal{L}(Data_{IH}|Template_{NH})}$$



MultiNest

- We use the MultiNest algorithm (Feroz et al. 0809.3437) to find the maximum in multidimensional likelihood space
  - At the beginning ~75 points are chosen randomly
  - Then new points are chosen based on correlations between previous points and the calculated likelihood values
  - handles multiple modes natively

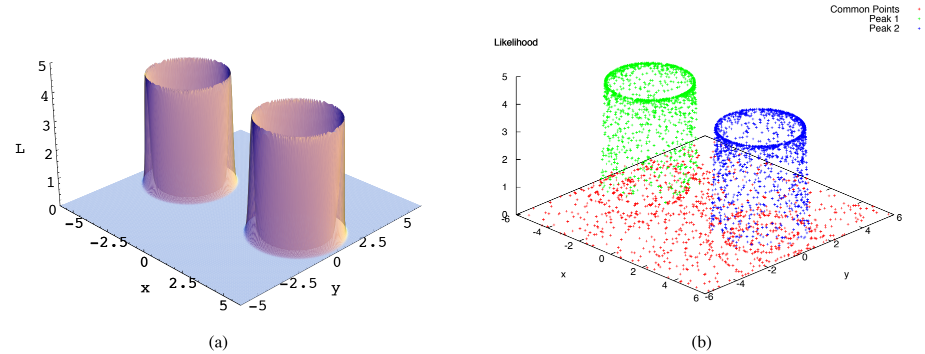


Figure 6. Toy model 2: (a) two-dimensional plot of the likelihood function defined in Eqs. (32) and (33); (b) dots denoting the points with the lowest likelihood at successive iterations of the MULTINEST algorithm. Different colours denote points assigned to different isolated modes as the algorithm progresses.

- Our likelihood for a given hypothesis is calculated by the Poisson probability to have measured a charge at one position and time relative to what is expected from simulated tables
- We reconstruct events with hypothesis of ν_μCC interactions [8 parameters]:
  - Interaction position and time
  - μ track length and direction
  - Hadronic cascade energy

PINGU Sensitivity

- Based on
  - 3 years of data
  - muon tracks only
  - used worse resolutions but better PID than we now have
  - consistent with our current estimates

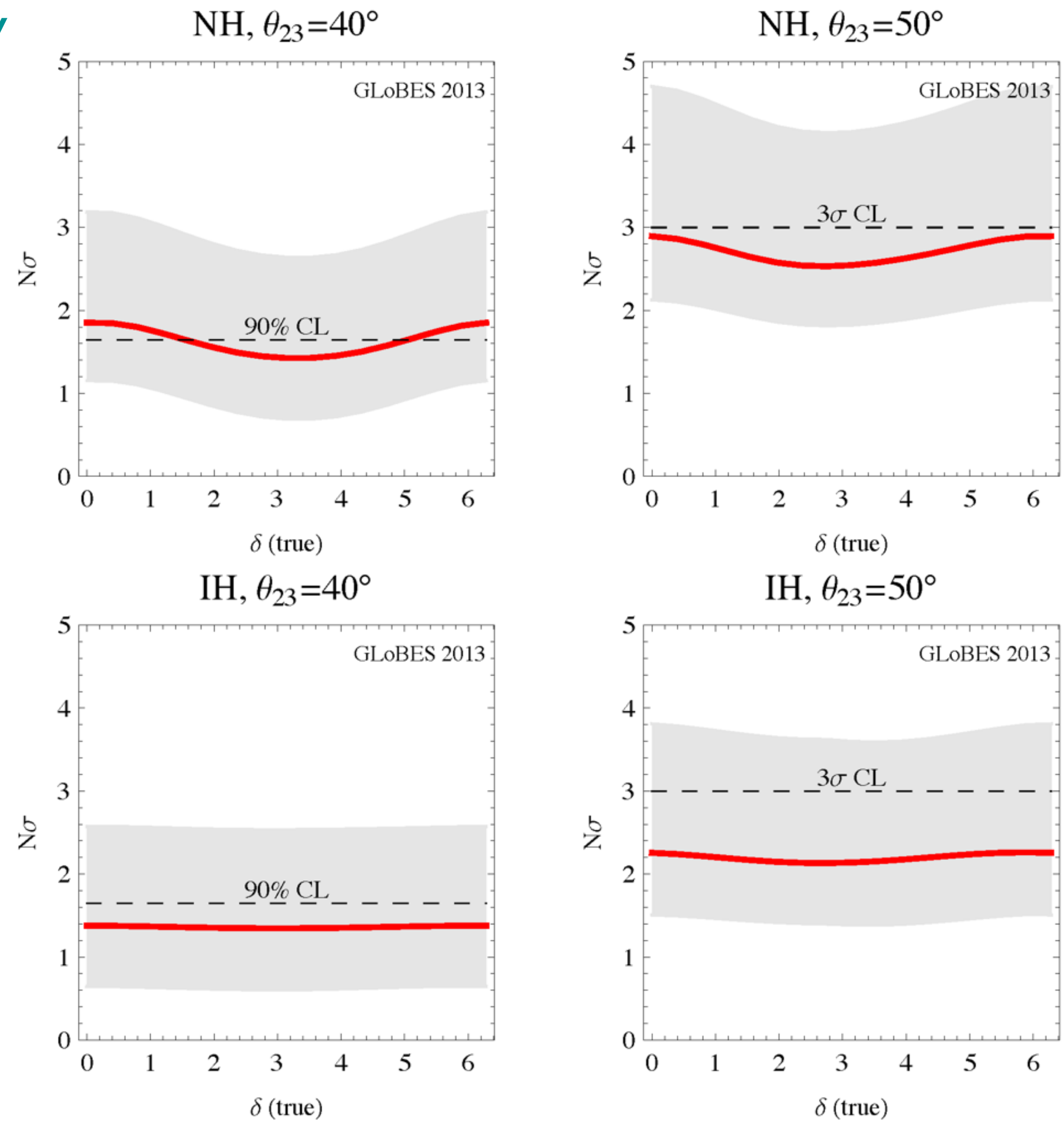


Figure 4: The number of sigma (Nσ) for the mass hierarchy discovery as a function of the true δ for the different (true) hierarchies (rows) and octants (columns), as given in the plot captions, for three years of data taking. The solid curves correspond to the default setup in Table 1, the shaded region shows the impact of systematics between optimistic (upper end) and conservative (lower end).

Winter 1305.5539

Combined Measurements

- Combination of PINGU and Beams+Reactor experiments is needed to reach 5σ for all values of δ
- Improvement can go beyond pure statistical

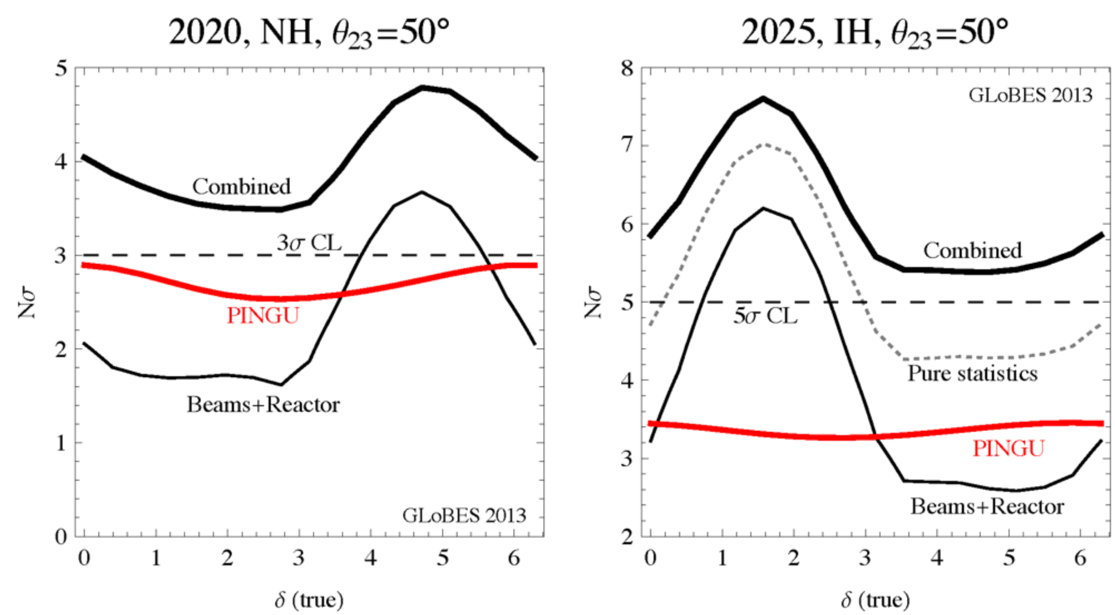
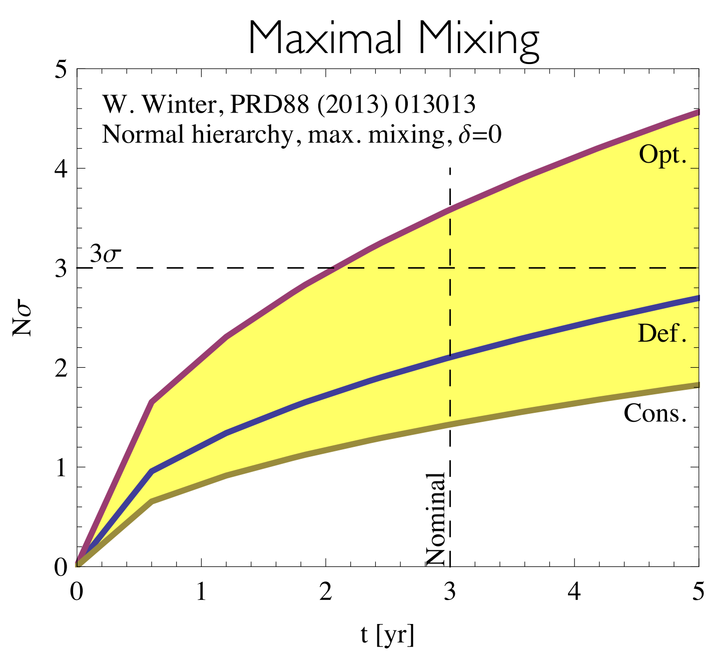


Figure 6: Number of σ for the hierarchy discovery as a function of δ for two different scenarios for PINGU (three years, left panel and eight years, right panel, respectively), beams and reactor experiments (scenario 2020, left panel, and 2025, right panel, respectively), and their combination. In the right panel, the hypothetical pure combination with the χ^2 added after minimization ("Pure statistics") is shown as well as dotted curve, to illustrate the synergy.

Winter 1305.5539



Combined Measurements

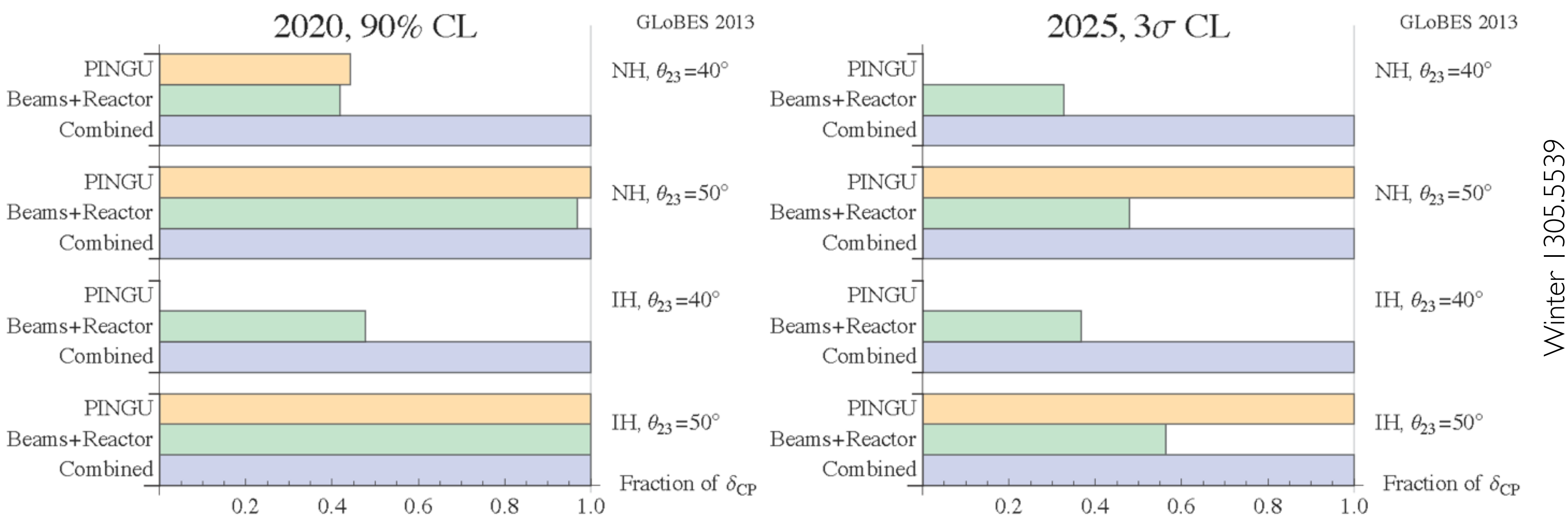
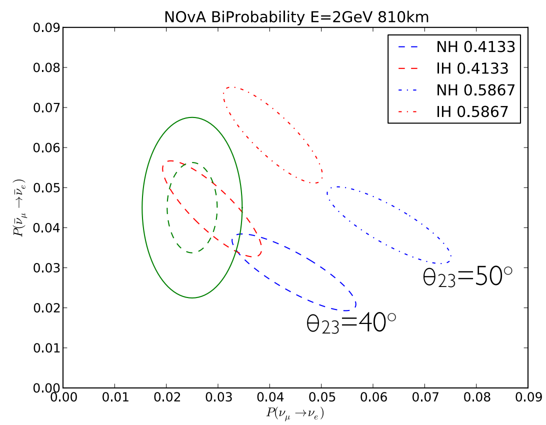


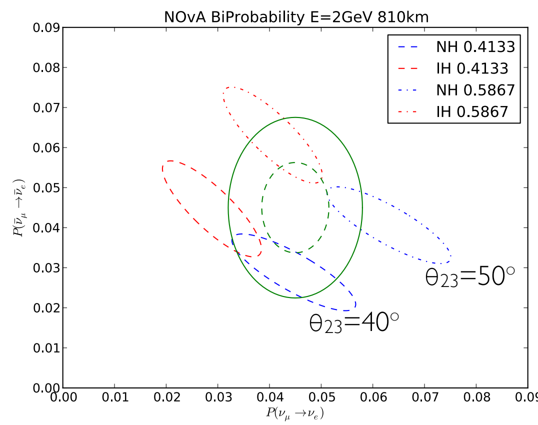
Figure 7: The fraction of δ for which the mass hierarchy can be discovered in 2020 (left panel, 90% CL) or 2025 (right panel, 3σ CL). The different bar groups correspond to different (true) hierarchies and θ_{23}, the individual bars to PINGU (three years, left panel and eight years, right panel, respectively), beams and reactor experiments (scenarios 2020 and 2025, respectively), and their combination.

NOvA, PINGU and δ_{CP}

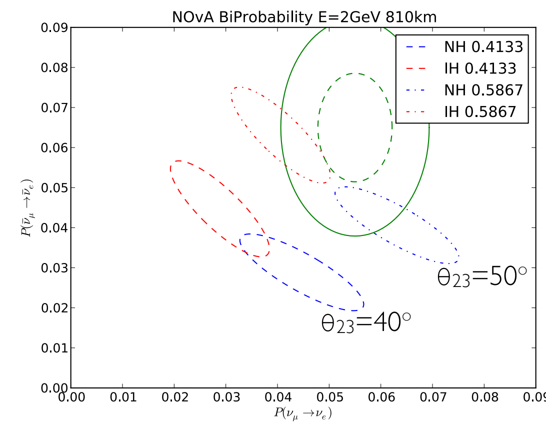
- Explore impact of knowing NMH at several selected points



If PINGU says NH, good δ_{CP} and octant resolution for NOvA



If PINGU says NH, improves NOvA's δ_{CP} measurement



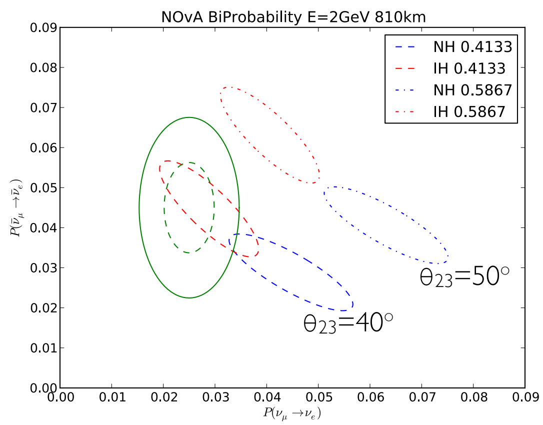
If PINGU says NH, good δ_{CP} and octant resolution for NOvA

		fraction of δ_{CP} within 2σ	fraction of δ_{CP} within 2σ	fraction of δ_{CP} within 2σ
$\theta_{23}=40°$	Unknown NMH	0.68	0.87	0.00
	NH	0.14	0.57	0.00
$\theta_{23}=50°$	Unknown NMH	0.00	0.89	0.90
	NH	0.00	0.36	0.46

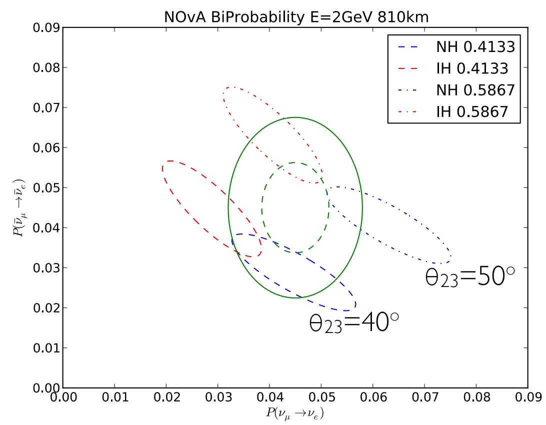
NOvA error ellipses: M. Messier, R. Patterson; theoretical curves based on Nunokawa et al. 0710.0554

NOvA, PINGU and θ_{23}

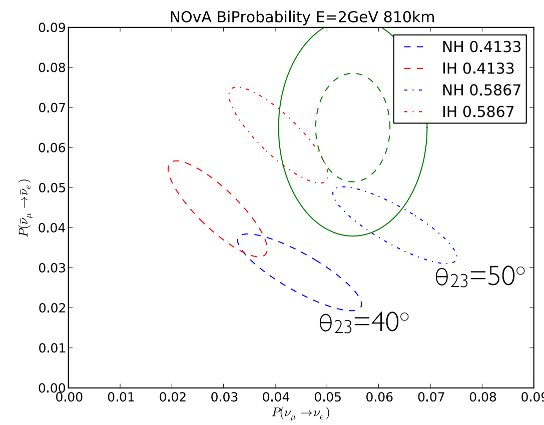
- Explore impact of knowing NMH at several selected points



If PINGU says NH, good δ_{CP} and octant resolution for NOvA



If PINGU says NH, improves NOvA's δ_{CP} measurement

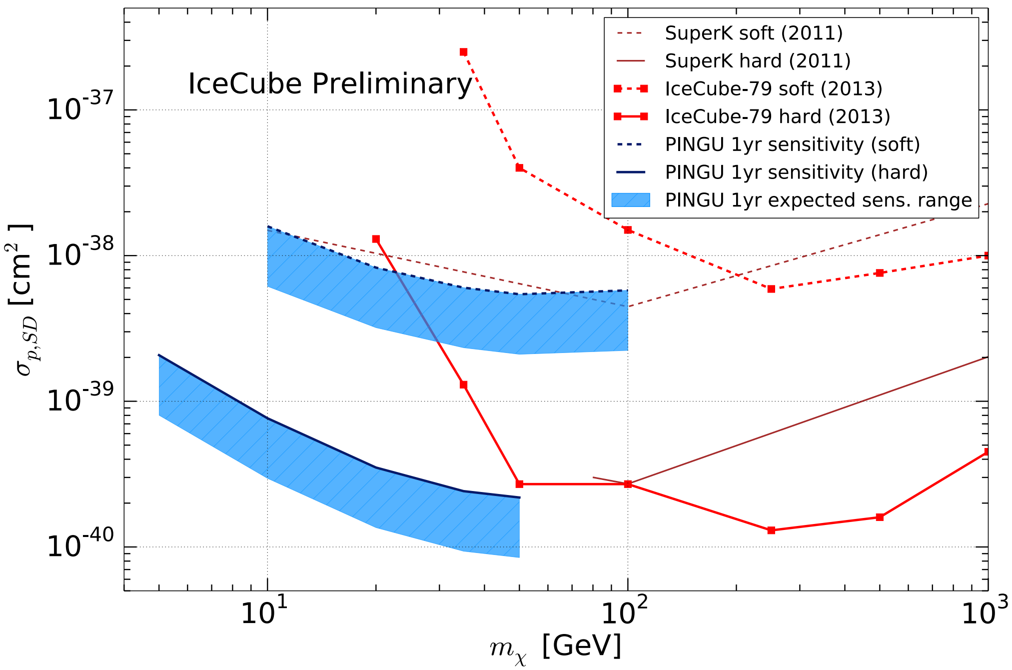


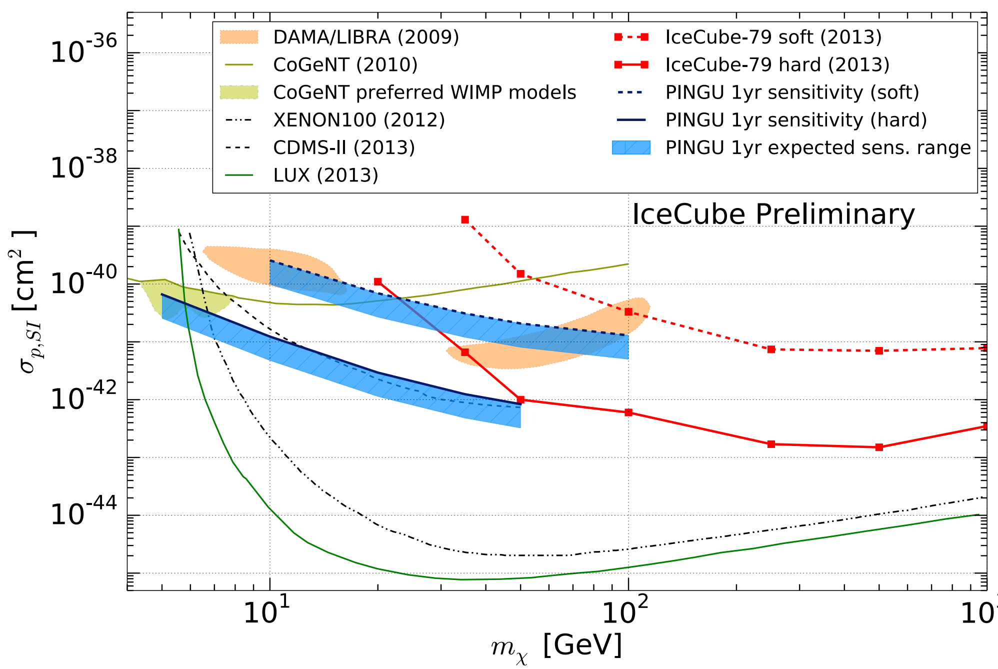
If PINGU says NH, good δ_{CP} and octant resolution for NOvA

		MinDist[(P,Pbar)→(δ_{CP} ellipse)]	MinDist[(P,Pbar)→(δ_{CP} ellipse)]	MinDist[(P,Pbar)→(δ_{CP} ellipse)]
$\theta_{23}=40°$	Unknown NMH	0.2σ	0.9σ	2.6σ
	NH	1.7σ	0.9σ	2.6σ
$\theta_{23}=50°$	Unknown NMH	2.6σ	0.6σ	1.0σ
	NH	5.4σ	1.0σ	1.1σ

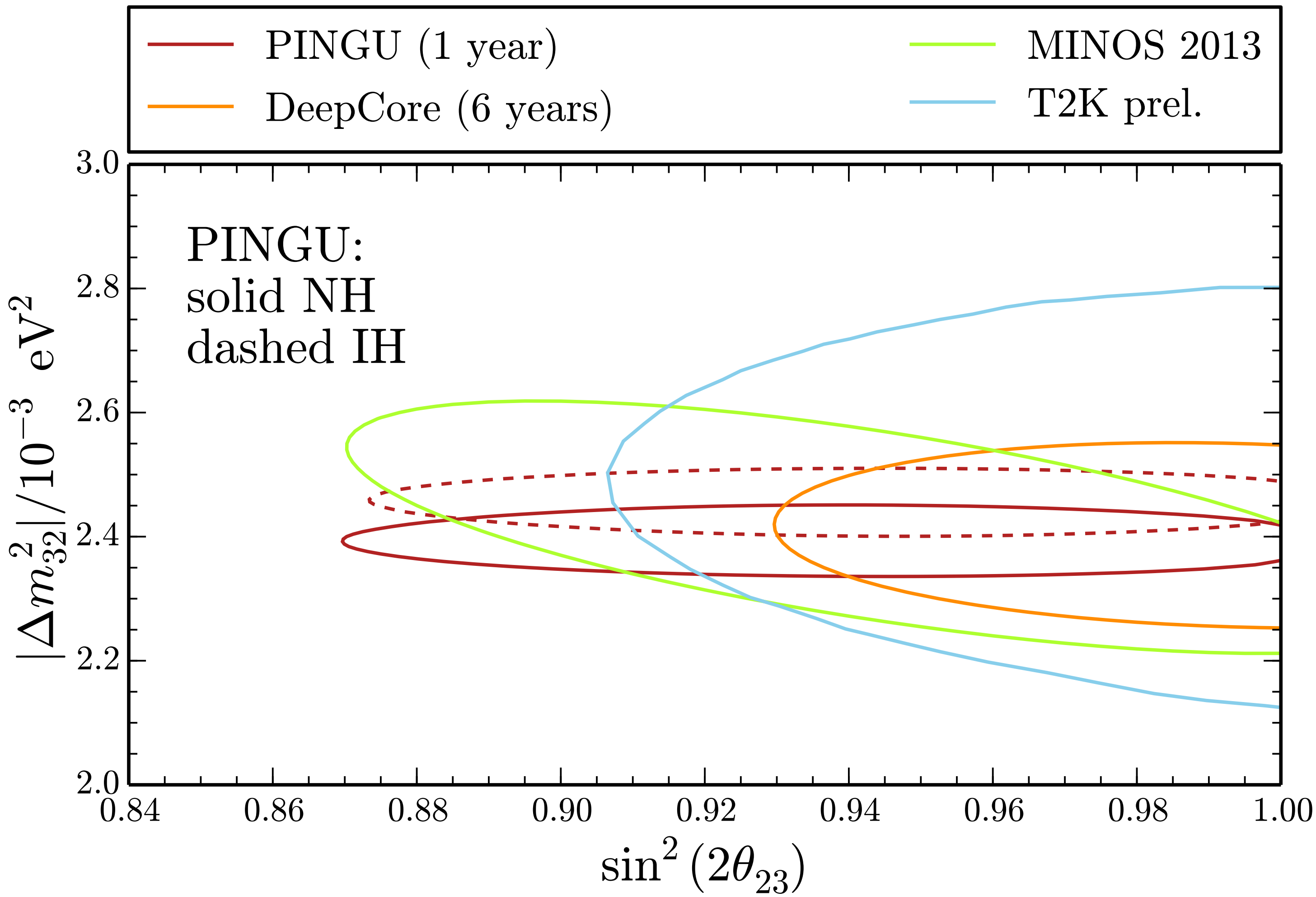
NOvA error ellipses: M. Messier, R. Patterson; theoretical curves based on Nunokawa et al. 0710.0554

PINGU and WIMPs





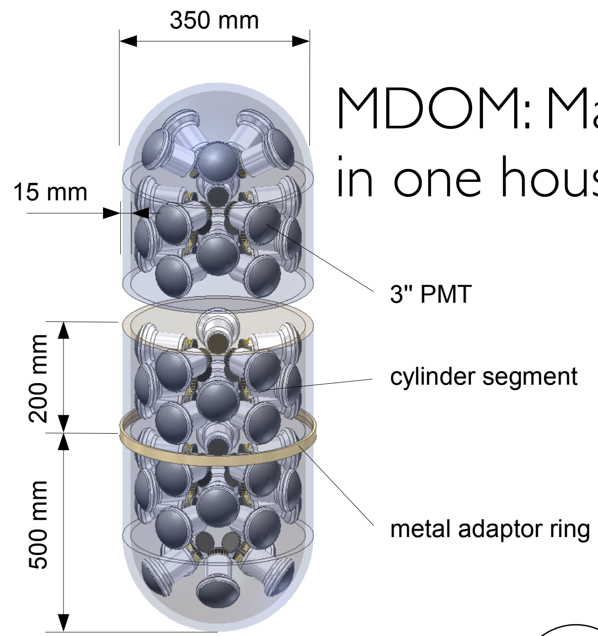
PINGU and ν_μ Disappearance



Notes:
20-string geometry, old event selection, old reconstruction criteria used

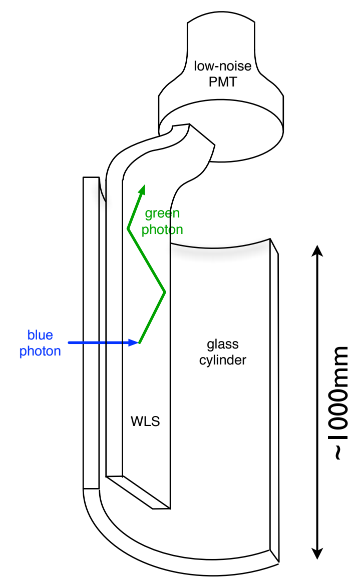
R&D

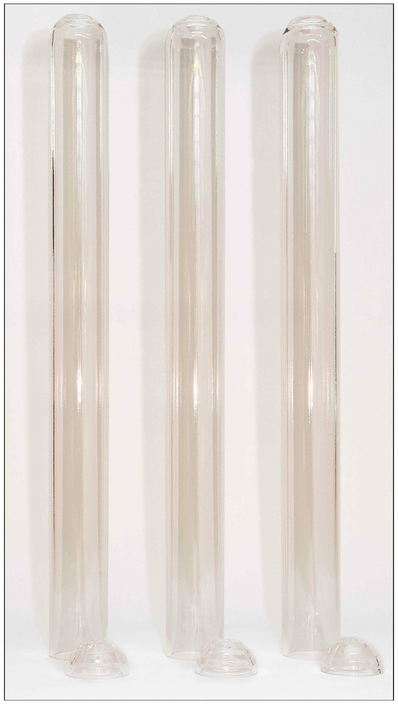
- Plan to deploy several R&D modules with PINGU
- Aim: Vet modules for megaton-scale in-ice Cherenkov ring imaging detector with low noise and threshold $E_{\nu} \sim 1$ GeV



MDOM: Many 3" PMTs in one housing

WOM: Wavelength-shifter tubes, PMT at end(s)

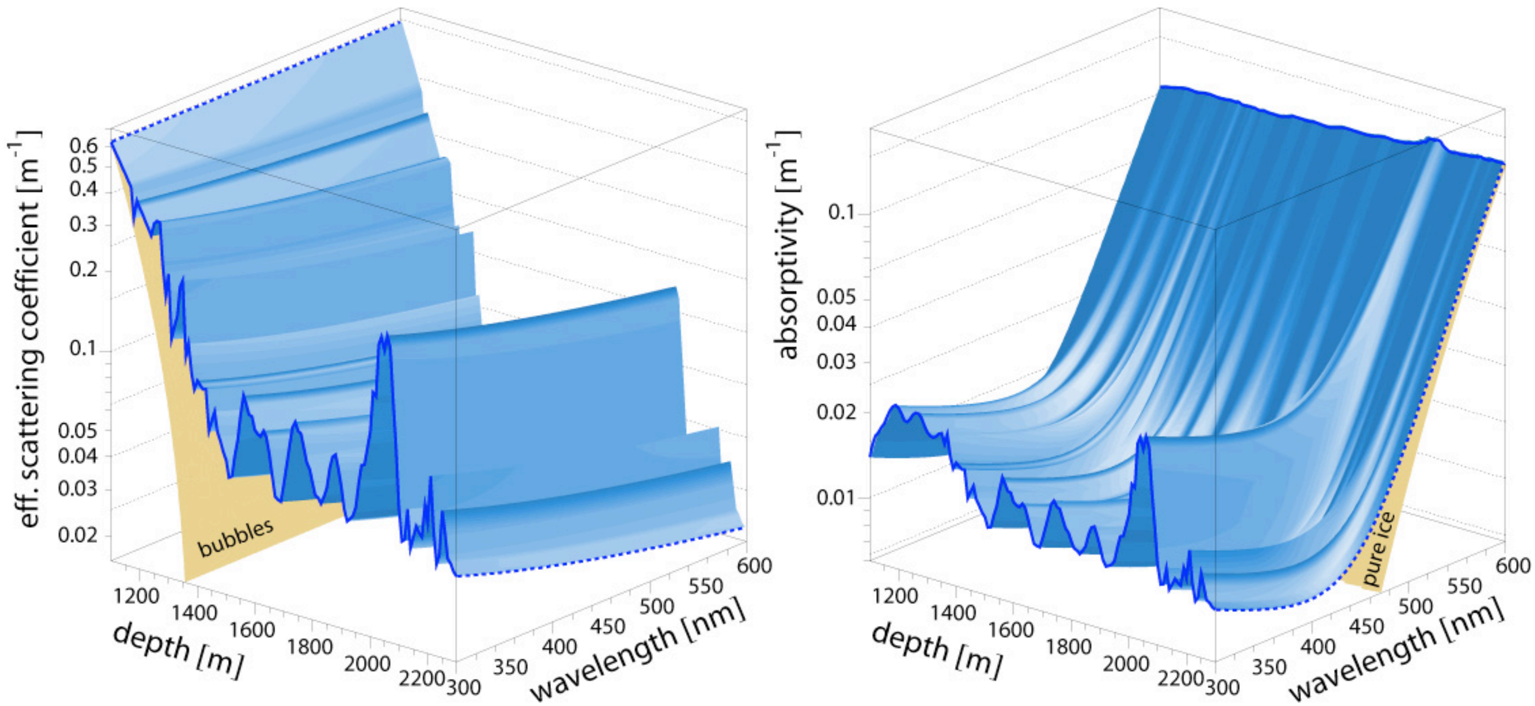




Quartz housings

Ice Properties

- Depth dependence of λ_{eff} and λ_{abs} from *in situ* LEDs
- Ice below 2100 m in DeepCore fiducial region <u>very</u> clear
  - $<\lambda_{eff}>$ ~ 47 m, $<\lambda_{abs}>$ ~ 155 m



- Constant temperature ~ -35C

Systematics

- Incorporated with Fisher parametric approach
  - Verified with all systematics via Asimov
  - Verified with some systematics via LLR
- Two broad classes of systematics
  - Physics-related (e.g., measured uncertainties in oscillation parameters)
  - Detector-related (e.g., energy scale uncertainty)

Young Snowmass

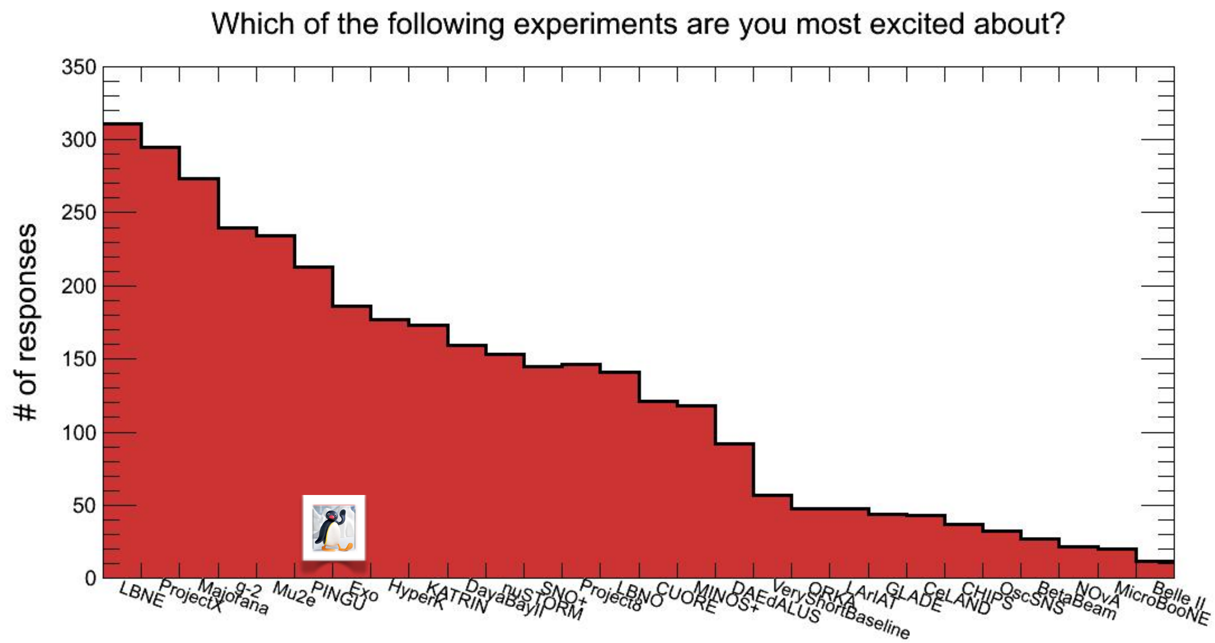


Figure 35: The respondent was asked to select the most exciting experiments from the non-exhaustive list provided. The respondent could select more than one.

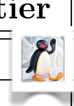
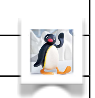
	Cosmic Frontier	Theory Frontier	Energy Frontier	Intensity Frontier
1	PINGU 	Majorana	Project X	LBNE
2	Majorana	g-2	LBNE	Project X
3	Exo	Mu2e	g-2	nuStorm
4	Sno+	LBNE	Mu2e	PINGU 
5	Katrin	HyperK	Majorana	HyperK
6	LBNE	Exo	Exo	Majorana

Table 1: The top six Intensity Frontier experiments respondents were excited about, broken down by their current frontier.

Answers to P5 Follow-up Questions

- What are the timelines in the two scenarios (with facility MREFC or "standalone")?
  - Short answer: the timelines from start of funding are the same.
    - In facility scenario, PINGU would be fully constructed first, followed by (e.g.) a high energy extension (HEX)
  - Apart from ~5 yr construction time, obvious main factor affecting PINGU completion date is actual start date
    - Facility MREFC: several years between submission→approval.
      - Bridge R&D funding could speed things up.
    - Alternative: standard proposal (could be faster).
  - Newly-appreciated fact: Minimum amount for MREFC is ~$130M (Jim Whitmore)
    - PINGU+HEX surpass this easily
    - PINGU standalone is *below* MREFC threshold, but PINGU may be too expensive for NSF's standard program (including the new Mid-Scale Fund).
    - Note: for a regular non-MREFC proposal, should subtract ~$20M (polar ops) from total.
      - NSF GEO OPP assumes this expense out of its operations fund

Answers to P5 Follow-up Questions

- Alternative funding scenarios
  - In contrast to IceCube physics, PINGU physics is squarely in the core mission for DOE
  - We should explore the possibility of (quicker) inter-agency funding
    - ~\$25M DOE, ~\$25M foreign, ~\$35M NSF PHY, (~\$20M NSF OPP) (*roughly*)
    - Spread out over 3-5 years, annual funding levels are reasonably low
    - P5 endorsement of DOE involvement in PINGU would be very helpful
      - NSF-funded DOE-Laboratory personnel designed and fabricated IceCube electronics
- Electronics design and drill refurbishment for a standalone PINGU would directly carry over to a future high energy extension
  - would reduce time to completion for HEX by ~2 years relative to Facility MREFC funding start
  - would reduce the cost and retire some risk of the HEX MREFC

Answers to P5 Follow-up Questions

- What are the systematic uncertainties considered in the atmospheric flux, specifically related to the angular dependence of the signal?
  - Short answer: Studied in both Fisher and Asimov analyses:
    - Fisher: zenith-dependent error in V_{eff} (degenerate with error in angular distribution of atm. flux) – impact so small it was neglected in our estimate
    - Asimov: systematic bias in detector pointing – again, minimal impact
    - Consistent with the observed lack of dependence of the energy and zenith angle resolutions vs. true zenith angle (see plots at end)
  - Measurement of angular dependence at higher energies (no oscillation) is a powerful constraint on these systematics
    - In future can also use downgoing neutrinos as additional constraint

Answers to P5 Follow-up Questions

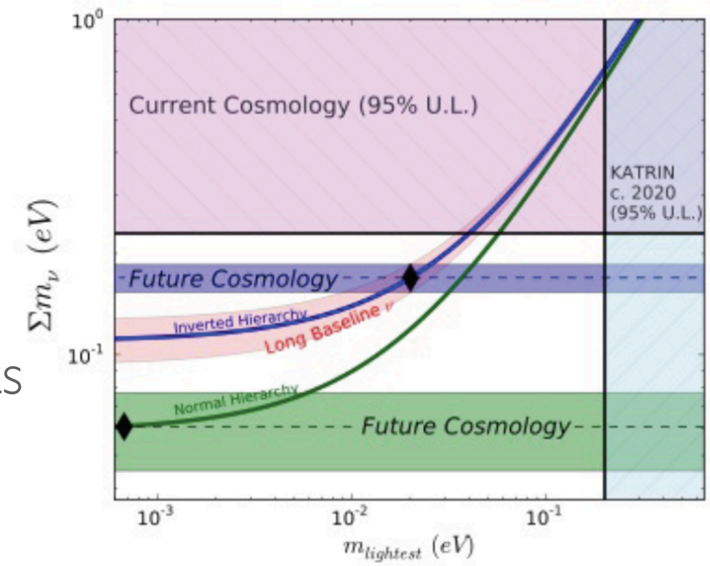
- What are the systematic uncertainties considered in the atmospheric flux, specifically related to the angular dependence of the signal?
  - Summary of systematics related to atmospheric flux:
    - Variation of spectral index (±0.05 on -2.65)
      - degenerate with E-dependent scale error in A_{eff}
    - Independent scale factors for neutrino and anti-neutrino fluxes
  - Have not yet studied, but will soon, independent flux scale factors for ν_e and ν_μ

Answers to P5 Follow-up Questions

- What are the systematic uncertainties considered in the atmospheric flux, specifically related to the angular dependence of the signal?
  - Follow-up on energy scale question posed on Monday
    - Can use minimum ionizing muons as an absolute calibration point
    - New calibration of IceCube using minimum-ionizing muons already yields 3% uncertainty (cf. 5% assumed for PINGU)
      - Uncertainty dominated by hole ice
      - PINGU has plan to degas and filter drill water, improving hole ice
    - Dominant impact may be hadronic vertex physics at low E
      - Study beginning

Answers to P5 Follow-up Questions

- If the NMH is determined first elsewhere, what is the impact on the physics potential of PINGU?
  - There is no other neutrino experiment that can determine the NMH on the PINGU time scale *and* with dramatically higher significance (assuming prompt funding).
    - Another experiment, e.g. JUNO (Daya Bay II), might get to 3 sigma before PINGU, but we would require combination with PINGU (+NOvA) to reach 5 sigma
  - Cosmic surveys could measure NMH at high significance by ~2025(?)
    - PINGU is competitive in terms of time scale
    - PINGU is complementary: CMB measurements can rule out IH, but a high Σm may be NH; PINGU + Σm from CMB gives us m(lightest)



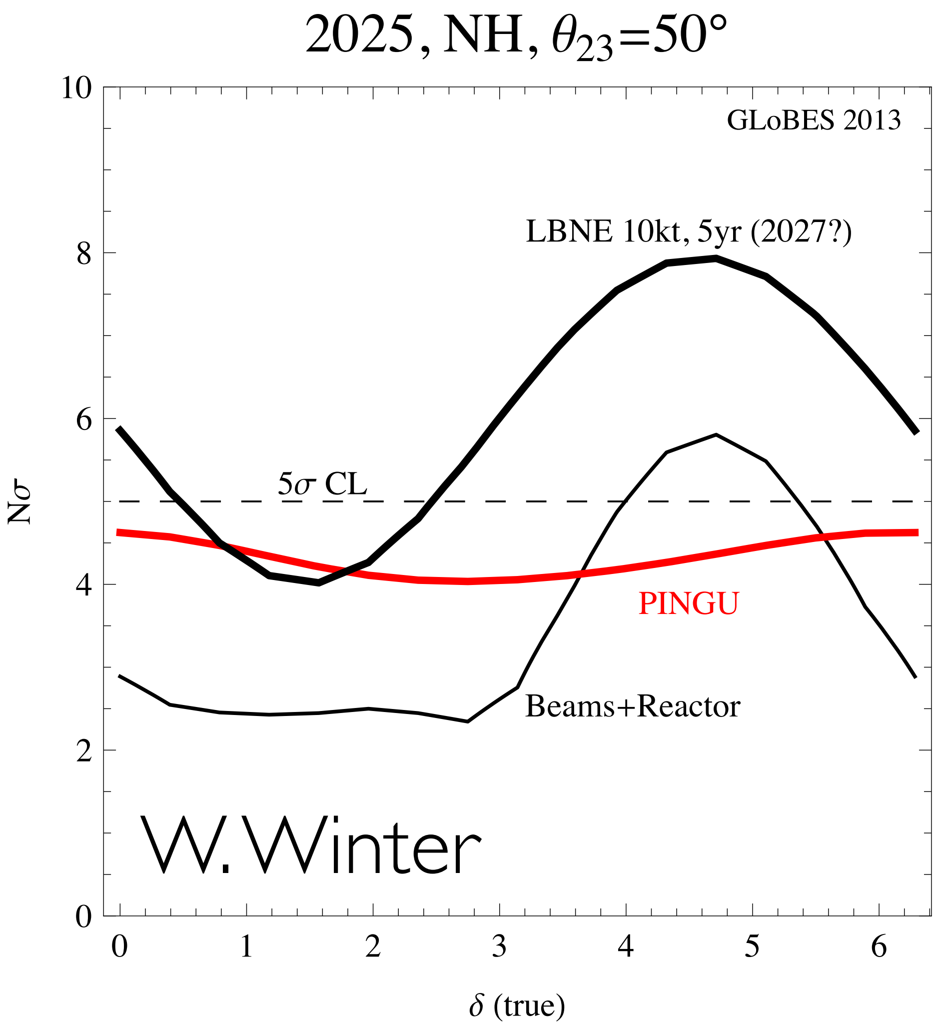
Answers to P5 Follow-up Questions

- If the NMH is determined first elsewhere, what is the impact on the physics potential of PINGU?
  - In neutrino oscillation physics, PINGU can do the following:
    - highly competitive muon neutrino disappearance with 1 yr of data
    - initial study: exclude maximal mixing at 5 sigma with 5 yrs of data
    - initial study: for the NH, distinguish correct θ_{23} octant by >3 sigma (1st octant) and >5 sigma (2nd octant)
    - although we have not yet studied ν_τ appearance, have every reason to believe that PINGU could make a high significance measurement in about one year (test unitarity of 3x3 mixing)

Answers to P5 Follow-up Questions

- If the NMH is determined first elsewhere, what is the impact on the physics potential of PINGU?
  - PINGU has sensitivity to solar and GC WIMPs down to about 5 GeV.
    - World's best SD sensitivity with 1 yr of data, begin to probe DAMA/LIBRA/CoGeNT regions in SI space
    - Solar WIMP signal offers least model-dependent search channel
    - No nuclear effects–all protons
  - Other science
    - PINGU+IceCube would have 2x sensitivity of IceCube alone to galactic SN neutrinos
      - PINGU could measure average SN neutrino energy 5x better than IceCube
    - Earth tomography
      - Exclude pure Fe core at 90% CL in 12 years

Combined Measurements

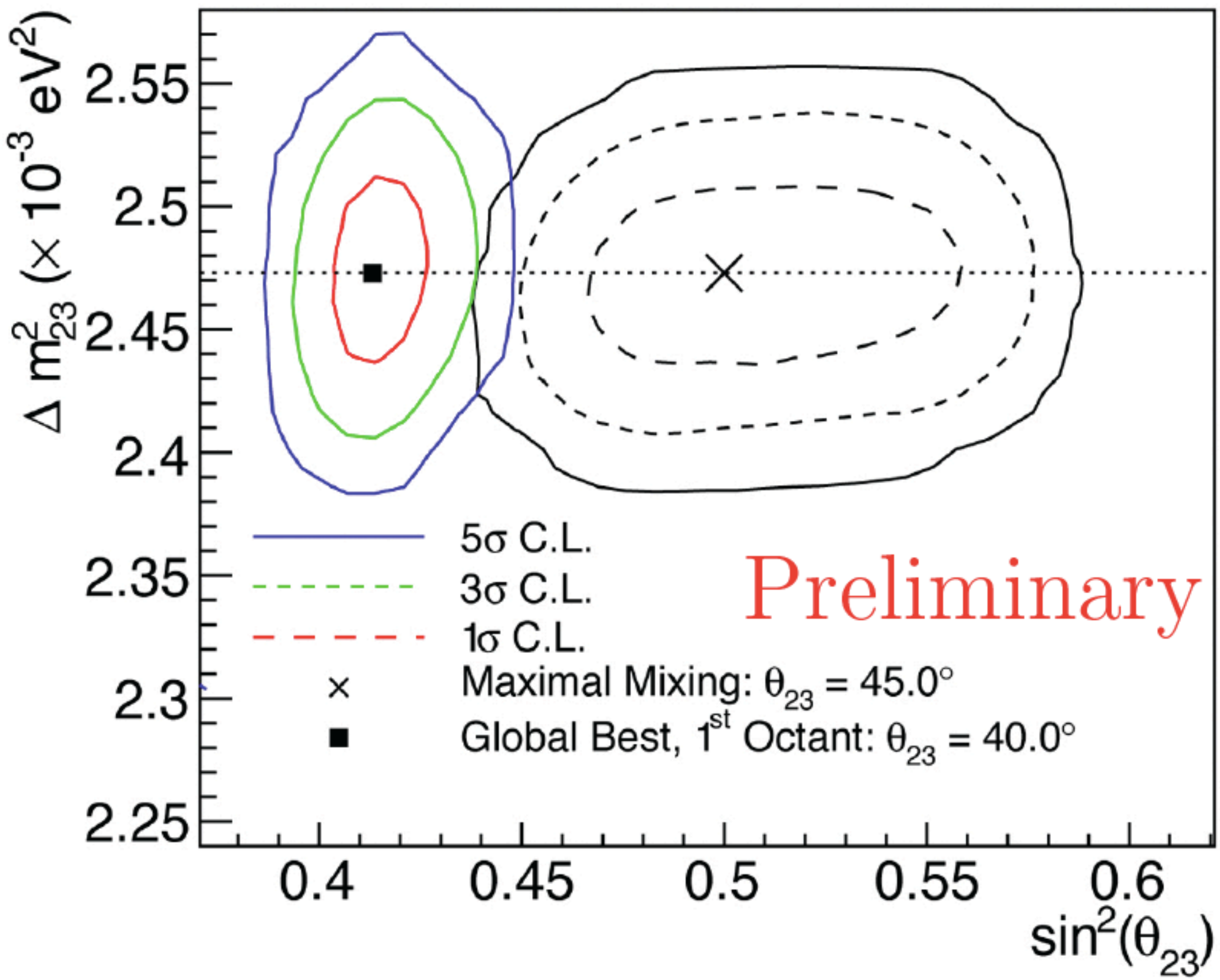


- PINGU line uses only ν_μ, but assumes very good PID.
- Second octant.
- 5 years of data.
- "Beams+Reactor" includes NOvA, T2K and JUNO.

How would foreknowledge of the NMH improve LBNE's measurement of δ_{CP}?

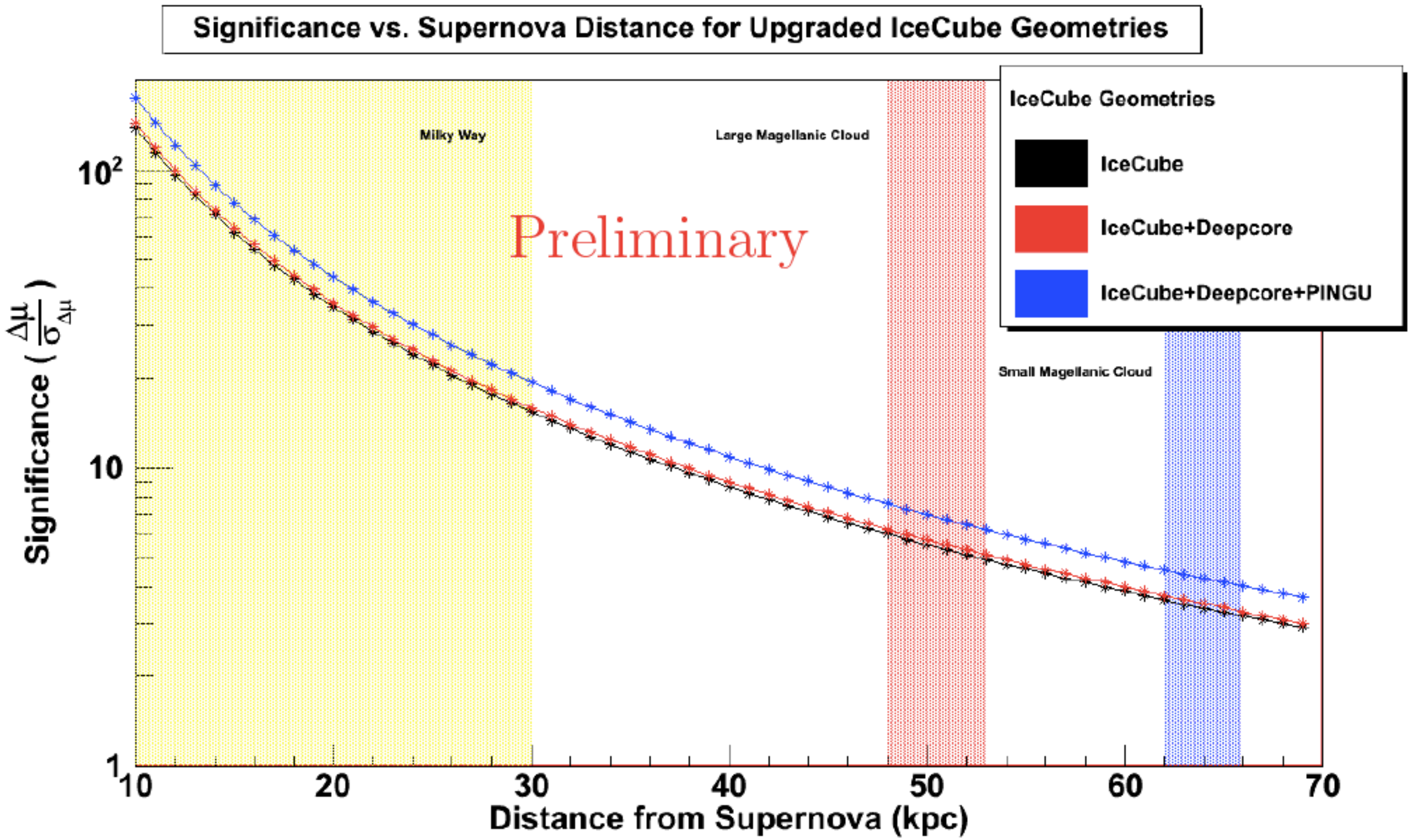
Additional Plots

Normal Hierarchy

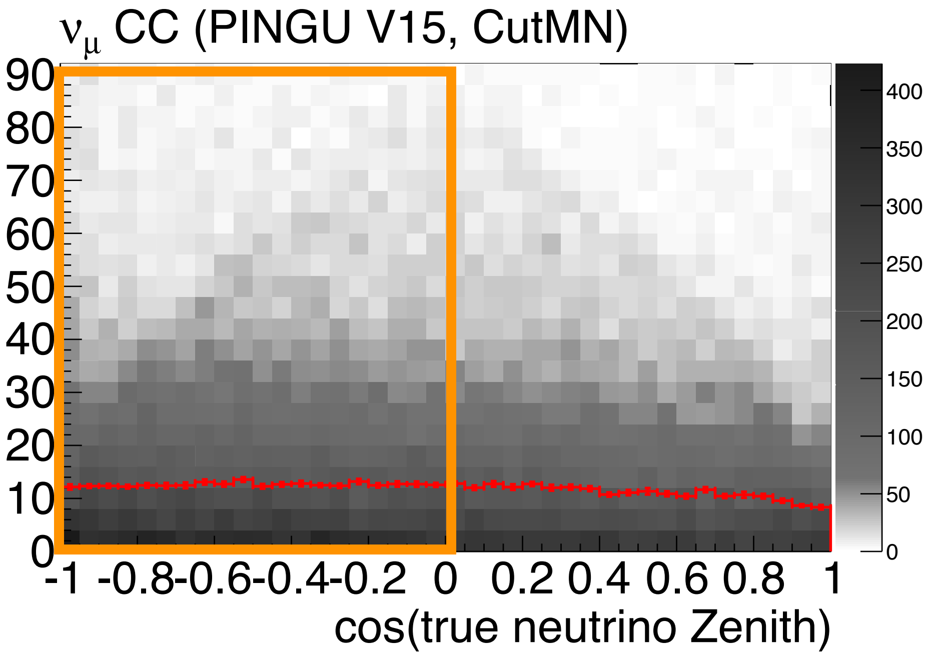


Systematics not yet fully evaluated.

Additional Plots



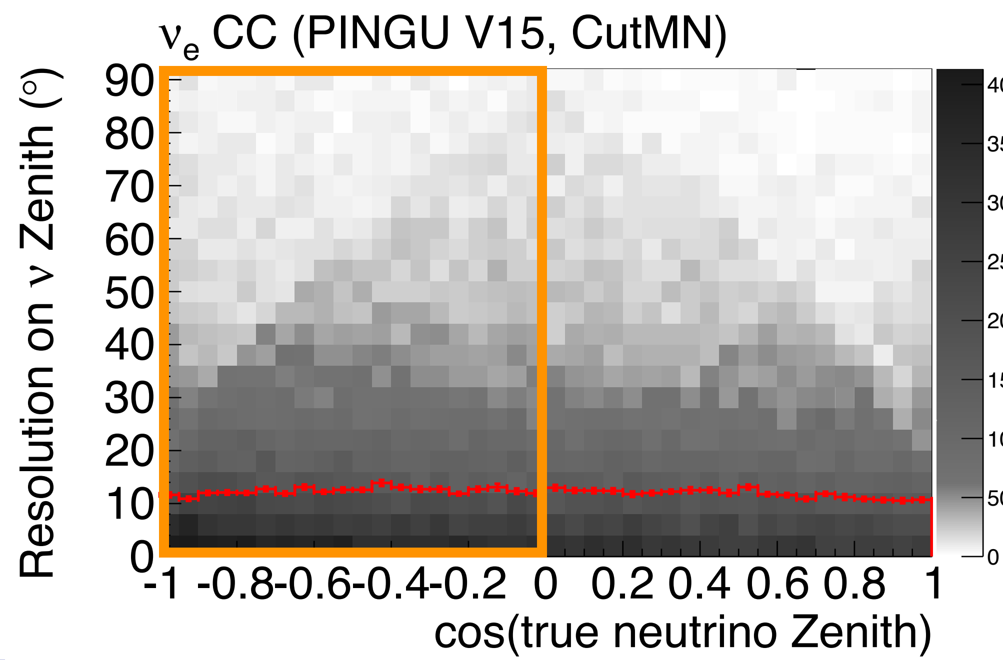
Zenith Angle Resolution vs. True θ



Red line is median

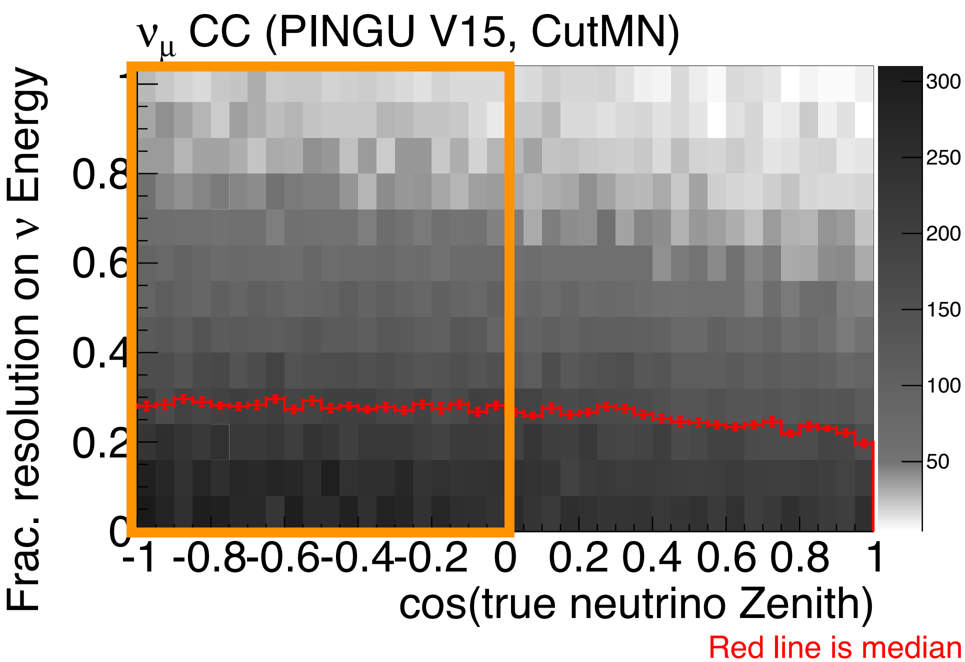
Muon neutrinos

Electron neutrinos



Red line is median

Energy Resolution vs. True θ



Muon neutrinos

Electron neutrinos